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Improvements to the Hunter Dose Tracking System

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Savannah River National Laboratory™
OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS

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EXECUTIVE SUMMARY

Since 1965, the Savannah River Site (SRS) has conducted deer hunts which are open to the general public. SRS performs field monitoring for cesium-137 (Cs-137) of each harvested animal to determine whether the animal may be released to the hunter. A new field system for measuring Cs-137 in the harvested animals has been developed. The system incorporates numerous enhancements compared to the original system. The original system was composed of two Ludlum Measurements scalar-driven 2 inch x 2 inch sodium iodide counters, while the new system is based on a single Ametek Ortec Digibase-driven 2 inch x 4 inch x 16 inch sodium iodide gamma spectrometer. The new system includes a series of easy-to-assemble stainless steel encapsulated lead shields. The combination of the larger detector size and lead shielding improved the detection limit of the new system by a factor of approximately three compared to the original system. This lower detection limit allows for a larger number of measurements to be directly compared to the laboratory results, in cases where animal portions have been sampled.

The new system eliminates the need for manual transcription of data from the scalar readout to paper and then to the Hunter Dose Tracking System (HDTS). An easy-to-use graphical user interface to control the system was designed, built, and adjusted with feedback from field personnel. Information on the specific animal/hunter is input into the computer and analysis results are now automatically sent from the spectrometer, combined with the animal specific information and loaded into the HDTS database. The new system provides immediate feedback to field personnel on whether to release or retain the animal.

The new system also eliminates the cumbersome manual calibration protocols of the original system. On the morning of the hunt, the system's calibration routines automatically adjust the system gain with a check source measurement. The calibration is then verified against a NIST-traceable standard. Each subsequent animal measurement is validated with a simultaneous measurement of an on-board quality assurance check source. There is a significant improvement over the quality assurance (QA) of the original system where system drift was not tracked, and QA hinged on periodic measurements of a check source after a set number of animal counts.

The system reports activity within the whole animal based on an innovative Monte-Carlo N-Particle (MCNP) model which scales the dimensions of the animal being measured to the animal type and weight. In addition, all spectra are stored for later retrieval, if necessary, whereas in the original system the data was not retrievable. For each measurement, the reported activity is also accompanied with the uncertainty of the measurement as well as the caveat as to whether the returned value is below the system's detection limit.

The results from developing and using this system are presented as well as recommendations on improvements to the overall field monitoring of the SRS hunts.

It is important to note that any errors with the sampling method and uncertainty in the activity measurements result in small changes to calculated dose and are well below any limits.

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LIST OF ABBREVIATIONS

CPM	Counts Per Minute
DOE	Department of Energy
DPS	Decays Per Second
FWHM	Full-Width Half-Max
HDTS	Hunter Dose Tracking System
MCNP	Monte-Carlo N-Particle
MDA	Minimum Detectable Activity
QA	Quality Assurance
QC	Quality Check
SRNL	Savannah River National Laboratory
SRNS	Savannah River Nuclear Solutions
SRS	Savannah River Site

1.0 Introduction

The Hunter Dose Tracking System (HDTS) exists to measure and record the radiation dose received by hunters who consume the meat of animals harvested at the Savannah River Site (SRS) and ensures those consumers do not receive dose that exceeds the DOE operator (SRNS) specified dose limits of 22 mrem annually and 360 mrem over a lifetime. These dose limits were chosen by the operator to ensure they stay within the limits specified by DOE order 458.1 (DOE, 2011), specifically sections 4.b.(1).(a), 4.e.(1).(a).3, and 4.e.(1).(c)

DOE order 458.1 Section 4.b.(1).(a) specifies:

> DOE radiological activities, including remedial actions and activities using Technologically Enhanced Naturally Occurring Radioactive Material (TENORM), must be conducted so that exposure of members of the public to ionizing radiation will:
>
> (a) Not cause a total effective dose (TED) exceeding 100 mrem (1mSv) in a year, an equivalent dose to the lens of the eye exceeding 1500 mrem (15 mSv) in a year, or an equivalent dose to the skin or extremities exceeding 5000 mrem (50 mSv) in a year, from all sources of ionizing radiation and exposure pathways that could contribute significantly to the total dose . . . .

DOE order 458.1 Section 4.e.(1).(a).3 specifies:

> 3 If it is suspected that any of the dose limits specified in paragraph 4.b.(1).(a) of this Order may be exceeded or the estimated TED for members of the public exceeds 25 mrem (0.25 mSv) in a year, then dose to the lens of the eye, skin and extremities must be evaluated.

DOE order 458.1 Section 4.e.(1).(c) specifies:

> Dose evaluations to demonstrate compliance with the public dose limit in paragraph 4.b.(1) of this Order and to assess collective dose must include the following:
>
> (c) The dose to members of the public from DOE-related exposure sources only, if the projected DOE-related dose to the representative person or MEI is 25 mrem (0.25mSv) in a year or less. If the DOE-related dose is greater than 25 mrem in a year, the dose to members of the public must include both major non-DOE sources of exposure (excluding dose from radon and its decay products in air, background radiation dose, occupational doses and doses due to medical exposures) and dose from DOE-related sources.

The largest contributor to dose from consuming animals harvested at the Savannah River Site is Cs-137 because it bio-accumulates. Therefore the activity of this radionuclide is used to calculate the received dose from the consumption of these animals. In the field, a conservative estimate of the concentration of Cs-137 in the meat of the animal is determined and the dose is calculated from the amount of meat to be released and the concentration in that meat. If this value plus any dose received previously is below the dose limits set by the SRS operator (22 mrem annual and 360 mrem lifetime), then the animal is released to the hunter (consumer) of that animal. The estimated dose from this animal is recorded and associated with a specific hunter (consumer), to track the received annual and lifetime dose. If an animal has activity that would create dose that exceeds either of these thresholds, it is not released.

2.0 Minimal Detectable Activity

The Minimal Detectable Activity (MDA) is the resolution limit of the system. It describes the point where any activity in a sample is indistinguishable, by the instrument, from the background. A series of Cs-137 spectra can be seen in Figure 5-3. The majority of harvested animals at SRS have spectra that fall between the yellow (Priscilla) and blue (Background) curves. The center of the spectrum, the Region of Interest (ROI), is the peak area. The Left and Right regions (outside of the horizontal limits) contain the background counts. See section 5.4 for further description of these terms.

For the new system, the MDA is calculated in counts per minute for each measurement, as described in (Currie, 1968):

$$MDA(cpm) = \frac{2.71 + 4.65\sqrt{Left_{Cs} + ROI_{bkg} + Right_{Cs}}}{Time\ (m)}$$

Where $Left_{Cs}$ and $Right_{Cs}$ are the sum of counts in the left and right areas of the sample measurement, respectively, and the ROI_{bkg} is the number of counts in the peak area when no sample is on the system. Time is the count time in minutes.

The MDA increases as background activity increases; increased shielding of the detector facilitated reduced MDA values. The MDA also increases as sample activity increases due to Compton scattering contributing to the number of counts in the Left region ($Left_{Cs}$).

3.0 Original HDTS

The original HDTS consists of separate hardware and software platforms. The hardware is two Ludlum Measurements scalar-driven 2 inch x 2 inch sodium iodide detectors mounted on a metal plate which is swung over and pressed against a harvested animal's haunch to measure the radiation, Figure 3-1. These detectors have a single channel analyzer which reports the sum of counts measured in a predefined range of energy corresponding to Cs-137.

Figure 3-1. The original HDTS.

The sum of counts, reported from each detector of the system, is transcribed onto paper and input by a field technician into a spreadsheet to calculate the average Cs-137 concentration. The dose

assigned to the hunter (consumer) is calculated from the average concentration and stored within the spreadsheet.

The quality assurance method of this system is based on periodic measurements of a check source after a set number of animal counts. It does not have a method to track system drift.

The system uses a linear calibration based on a series of six phantoms that relates detector response (in counts-per-minute) to concentration. SRNL-TR-2012-00120, (Dixon, 2012), fully documents the original system.

The MDA limit of this system is approximately 1.6 pCi/g. In 2016, 82% of the animals harvested at SRS were below this limit.

4.0 Prototype System

The first concept for a new detection system consisted of an integrated detector and dose tracking system. The hardware is a single Ametek Ortec Digibase-driven 2 inch x 4 inch x 16 inch NaI detector mounted in a steel box with lead bricks shielding the detector. The system is placed next to a harvested animal's haunch to measure the radiation, see Figure 4-1. The prototype system was tested in the spring of 2016.

Figure 4-1. The prototype system.

The prototype system had improved sensitivity when compared to the original system, due to the larger detector size and increased shielding. It is a multi-channel analyzer based system, which enables saving the spectra for troubleshooting and further analysis.

Besides utilizing a larger detector and increased shielding, the prototype system calculates the concentration in the animal by relating the measured counts per minute (CPM) to the results obtained from a Monte-Carlo N-Particle (MCNP) modeled system. In addition to the shielding, the correlation relationship from the MCNP model is the heart of the new system. A complete description of this model is found in SRNL-STI-2017-00293 (Brand, 2017) and a summary is described in section 5.6 of this document.

The Minimal Detectable Activity (MDA) limit of this system is approximately 1.2 pCi/g.

5.0 Production System (HDTS) – as built

An overview of the as-built system is described here. Complete system specifications and operating instructions are found in (Whiteside, HDTS 2017.0 Software Documentation, 2017) and (Whiteside, HDTS 2017.0 User Guide, 2017). The software QA document is (Whiteside, HDTS 2017.0 Testing and Verification Document, 2017).

5.1 Detector system

The production version of the system is based on the same Ametek Ortec Digibase-driven 2x4x16 NaI detector as used in the prototype system. Because of the improved shielding, as described below, the production system further decreases the MDA from 1.2 pCi/g to approximately 0.6 pCi/g.

5.2 Physical shielding

Based on user feedback, desire to further reduce background noise, and to easily move the animals to a defined location relative to the detector, a box with increased shielding and designed to be buried was constructed, Figure 5-1. The steel box dimensions are 15-1/4 inch W x 33-3/4 inch L x 7-1/4 inch" H. Five components (each of which are light enough to be handled by one person) containing encapsulated lead shielding and/or polyethylene detector supports are placed into the box. The assembly is covered by a Lexan lid with markings showing where to place the calibration source, small animals, and the animal haunches. All of the components are constructed and labeled so they must be oriented in the same direction for each hunt, ensuring a consistent system setup.

Figure 5-1. As-built HDTS shielding.

5.3 Setup and Calibration

Prior to measuring any animals, the system is readied for use through a series of steps that power on the detector, calibrate the detector, record the environmental background, and ensure the

system is performing adequately. After the detector is turned on (high voltage is applied) the detector is calibrated by placing a Cs-137 check source over the detector system, in the marked location. The system turns on the gain stabilization and counts for 30 seconds, which centers the peak at 662 keV. The background in the Cs-137 region of interest is measured by ensuring no sources are near the system and the system is operated for 1 minute. This counts-per-minute value is recorded in the software. Next the system counts the quality check (QC) phantom and calculates its activity.

The QC phantom is a certified 20 L solid in a 50 L LDPE bottle with an approximate decay corrected activity of 3.60 pCi/g. The mean difference in measured vs decay corrected certificate value of 20 field measured activities in 2016 was -0.07 pCi/g (-1.9%), with a standard deviation of 0.20 pCi/g (5.5%).

In order to pass the QC, the measured activity +/- the overall uncertainty must be within 16% of the certificate value. This 16% is the three standard deviations of the 2016 field measured phantoms and well below the 25% requirement of SRS 1Q-12-3. If the QC phantom is measured outside of this limit, two follow-up QC measurements must pass this check. If these fail, the user is alerted and the system shuts down. The CTF should review the control chart found under the Expert tab of the Detector control panel to determine the correct course of action.

Also included with the system is a Eu-155 check source that remains on the detector during the hunt. The half-life of Eu-155 is 4.76 years. After two half-lives, the system will alert the user to contact SRNL to evaluate the check source to ensure it is still producing an adequate number of counts. The counts per minute in the Eu-155 region of interest are recorded in the system during the QC phantom measurement. When measuring the animals, the software compares the counts of Eu-155 measured to this saved value and if these values differ by more than 7%, the system will prompt the user to recalibrate the system, using the Cs-137 check source. The reasoning behind this value is further described in section 5.5.

5.4 Region of Interest

To determine the counts per minute of activity, a region of interest (ROI) is defined. The recommended ROI size, as described in (Canberra, 2009), is calculated as three times the number of channels as the full-width-half-max (FWHM) of a Gaussian curve. We are defining the FWHM as two times the number of channels between the peak channel and the half-max right channel. The region of interest is centered on the peak channel and starts at the channel 3*FWHM/2 to the left of the peak channel. The net counts per minute is defined as the number of counts in the ROI less the sum of the number of counts in the left and right regions, where the left and right regions are each one half the number of channels as the ROI.

In the system, two regions of interest are defined. One is for Cs-137 and the other is for the on-board Eu-155 check source. The channels for these sources are determined for each individual detector and Digibase system. This is done by operating the detectors at the manufacture recommended high-voltages with a fine-gain adjustment such that the Cs-137 peak falls in channel 331, approximately 1/2 of the actual 662 keV of the photon and measuring the phantoms (Figure 5-2). For the Cs-137 peak at channel 331 the half-max channel is at channel 343. So the

region of interest for Cs-137 is from channels 295 – 367 as shown in Figure 5-3. The left and right regions are each 36 channels wide.

Our check source, Eu-155 has two gamma peaks, one at 87 keV and one at 105 keV, so the "peak" channel is actually set between these two peaks, at channel 54, and the half-max channel is channel 58. The region of interest is between channels 42-66. This allows coverage of both peaks but does not cover any X-ray peaks that may be in the spectra, as shown in Figure 5-4. The left and right regions are each 12 channels wide.

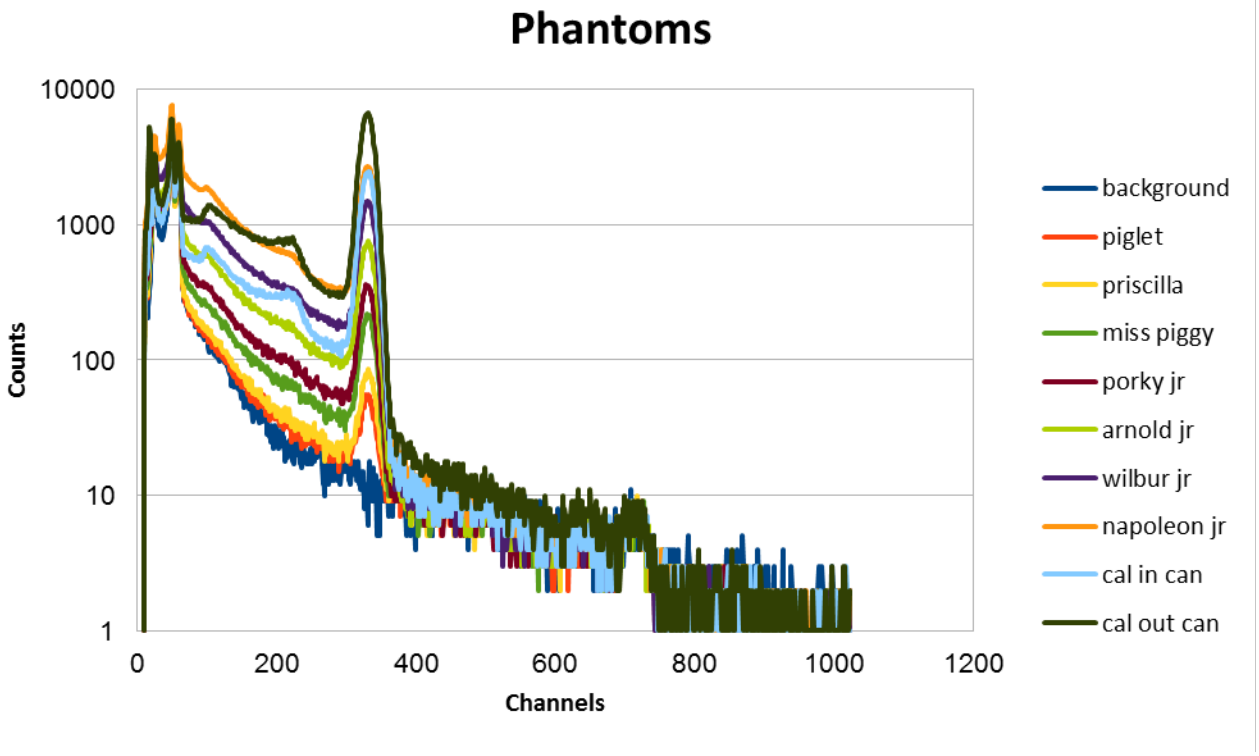

Figure 5-2. Spectra of phantoms and calibration sources.

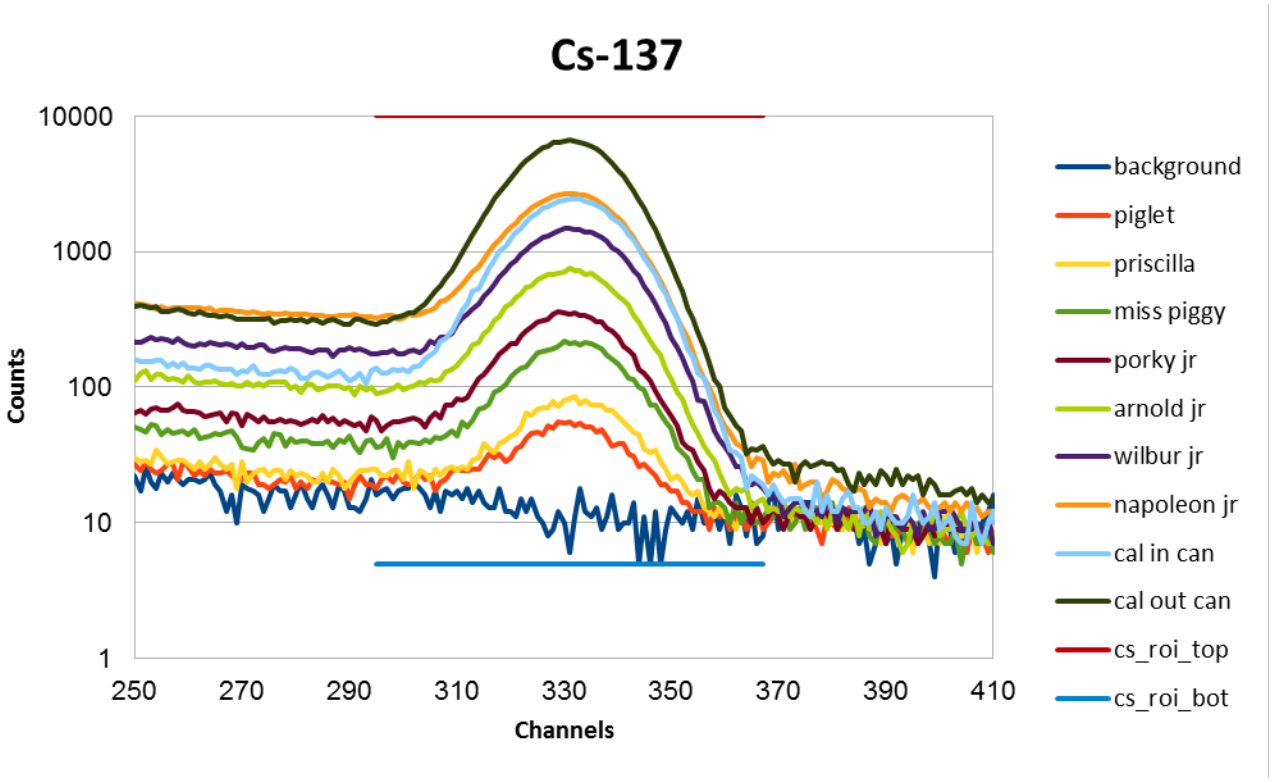

Figure 5-3. Zoom in on Cs-137 ROI.

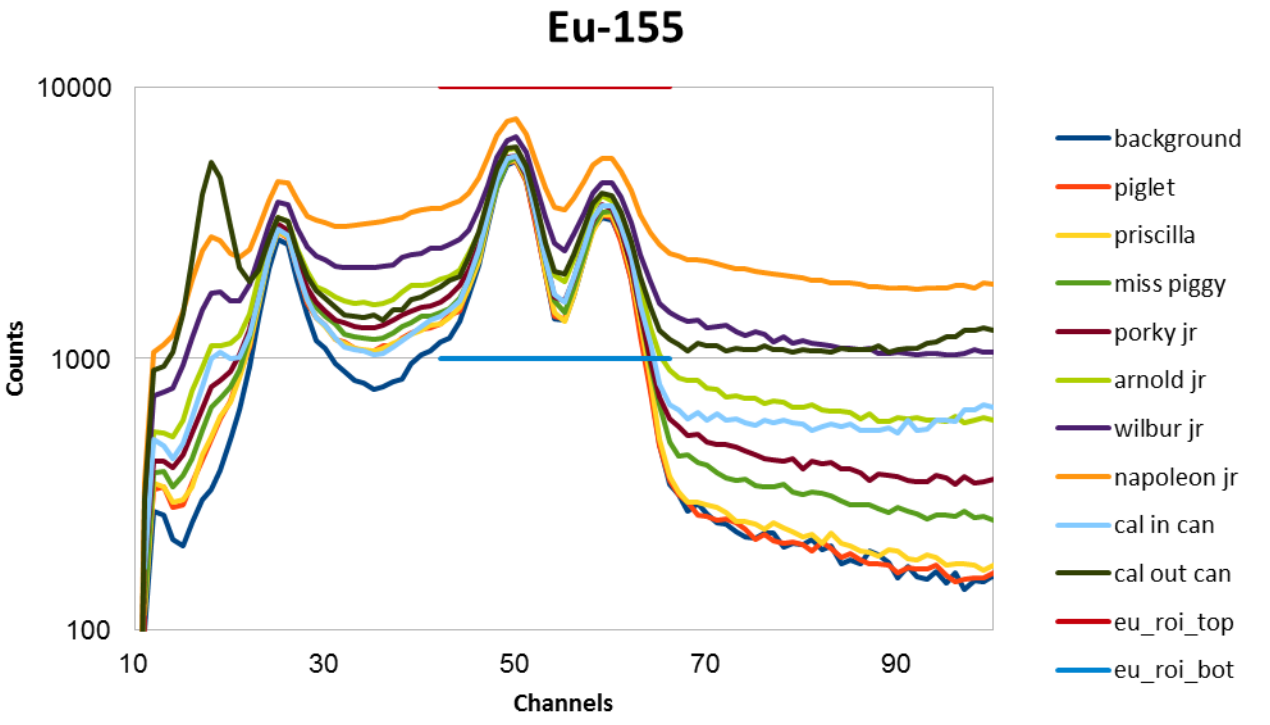

Figure 5-4. Zoom in on Eu-155 ROI.

5.5 Drift Control

It is well known that detector systems drift due to environmental factors, and these drifts could be significant enough to bias the results. Subsequently, drift controls were developed and incorporated into the system. To monitor system drift during the hunts, a Eu-155 on-board source was added to the system. After each animal is counted, the CPM of the onboard Eu-155 source is compared to the value measured when the QC phantom was measured at the beginning of the hunt. If this comparison differs by more than 7.0%, the system will reject the measurement and alert the user to re-run the system calibration.

To simulate system drift, the phantom "Porky Jr" was measured by the system at a series of gain settings and the relationship between Cs-137 CPM and Eu-155 CPM as a function of gain was developed. The measurement at each gain setting was performed three times. The correct gain multiplier setting is defined such that the Cs-137 peak is centered at channel 331 at the operating voltage of the detector, this value was 1.1715. The gain multiplier was then decreased in a series of steps to 0.90, as shown in Figure 5-5.

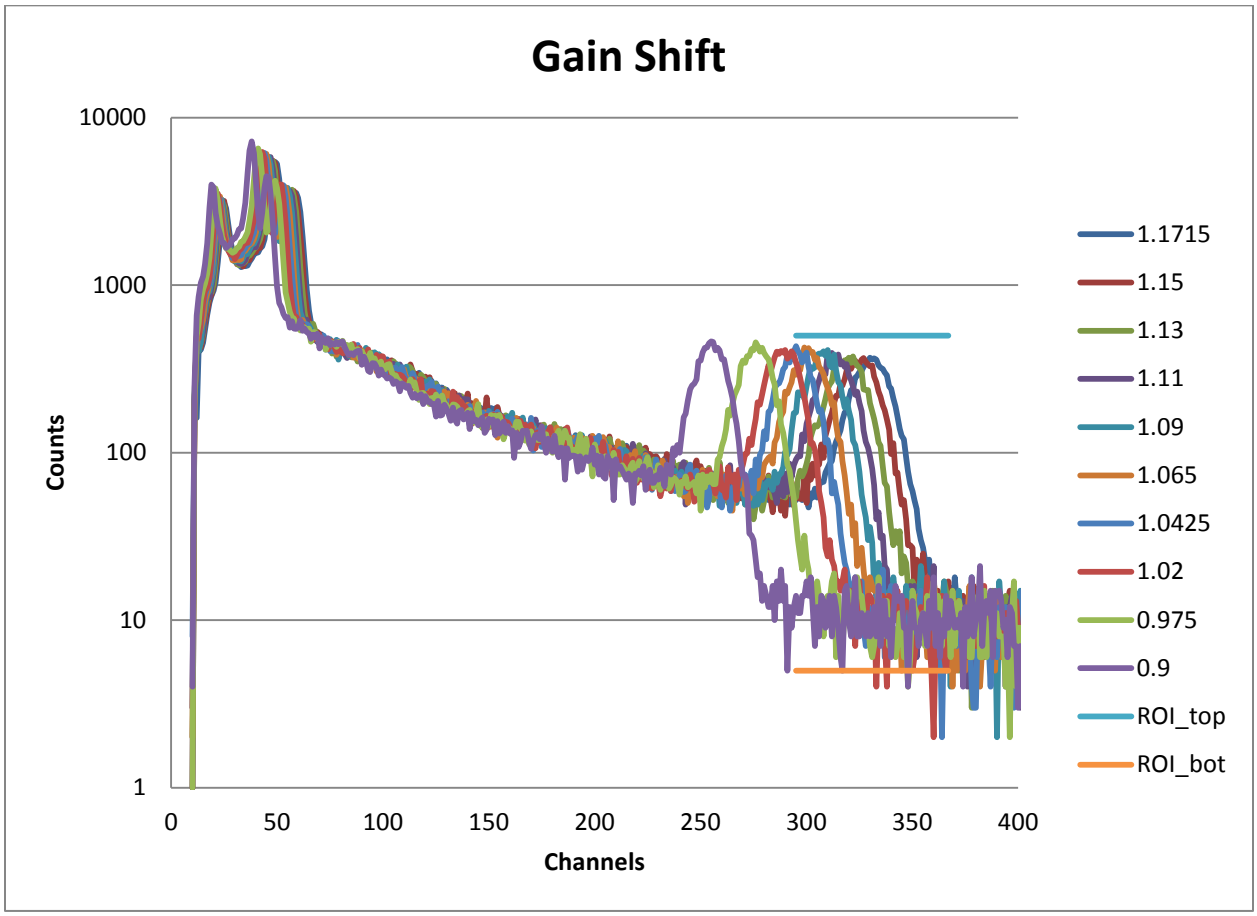

Figure 5-5. Gain shifted spectra of the phantom "Porky Jr".

The relationship between the percent change in the Eu-155 CPM and the Cs-137 CPM was plotted and determined by a best-fit relationship, as shown in Figure 5-6. This figure shows the relationship down to the gain multiplier value of 1.09 because at this point the Cs-137 CPM measured in the ROI is nearly 25% lower than actual.

In order to limit the uncertainty due to drift, we defined the drift limit of the Eu-155 CPM to be 7%. This contributes a maximum uncertainty to the Cs-137 CPM of less than 12%, which is incorporated in the reported measurement uncertainty. See the Measurement Uncertainty section for further discussion.

It was observed that when measuring high levels of Cs-137 activity (much higher than the release limit for animals) the barium x-ray arising from the Cs-137 decay could interfere with the spectral fitting of the Eu-155 gamma multiplet, as shown by the dark green "cal out can" line in Figure 5-4. Further, we saw spectral broadening due to Compton scattering in high activity phantoms. The spectra of all of the phantoms were examined to determine if either these x-rays or Compton effects would cause the Eu-155 CPM to ever exceed the 7% limit. All of the phantoms passed this examination, with Napoleon (which has an activity 600% greater than the release limit) causing the greatest "error" in the Eu-155 CPM measurement (6.25%), due to Compton scattering.

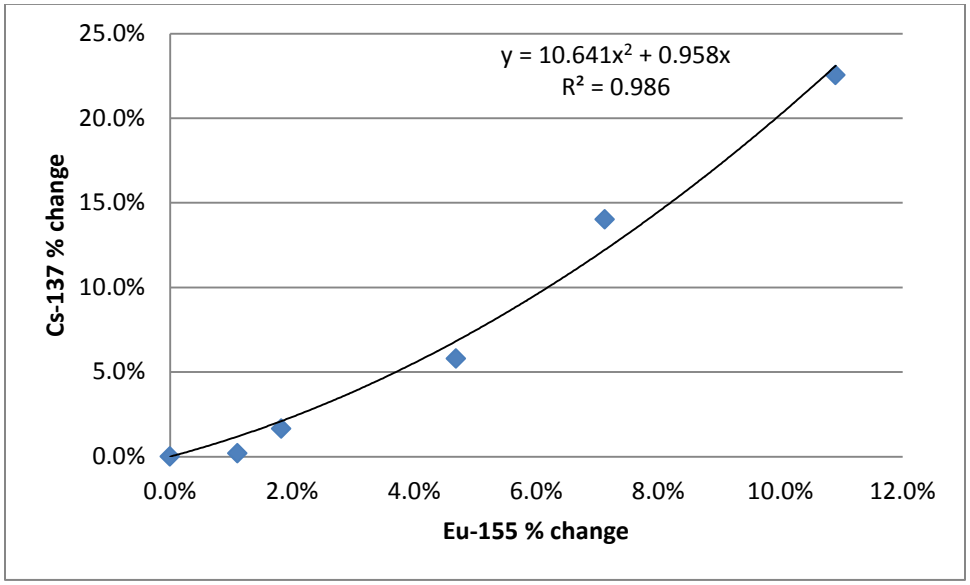

Figure 5-6. Relating percent change in Eu-155 CPM to percent change in Cs-137 due to gain shift

5.6 MCNP Model (Counts to Concentration)

To increase the accuracy of the measurements, a model was constructed using the MCNP (Monte-Carlo N-Particle) code. This code represents the detector, the shielded box, the animal, and the radiation source evenly distributed within an animal. In the model, Cs-137 is evenly distributed throughout the animal and the expected number of counts seen by the detector system is computed.

Multiple MCNP models were created and run, one model for each size animal. The volume of the animal in the model was based on the relationship between the chest girth and live weight. For each animal (DEER, HOG, TURKEY, COYOTE) between 6 and 9 models were created. The output from these models was used to create a fourth-order polynomial that relates CPM per 1pCi/g to live weight, as shown in Figure 5-7 and Table 5-1.

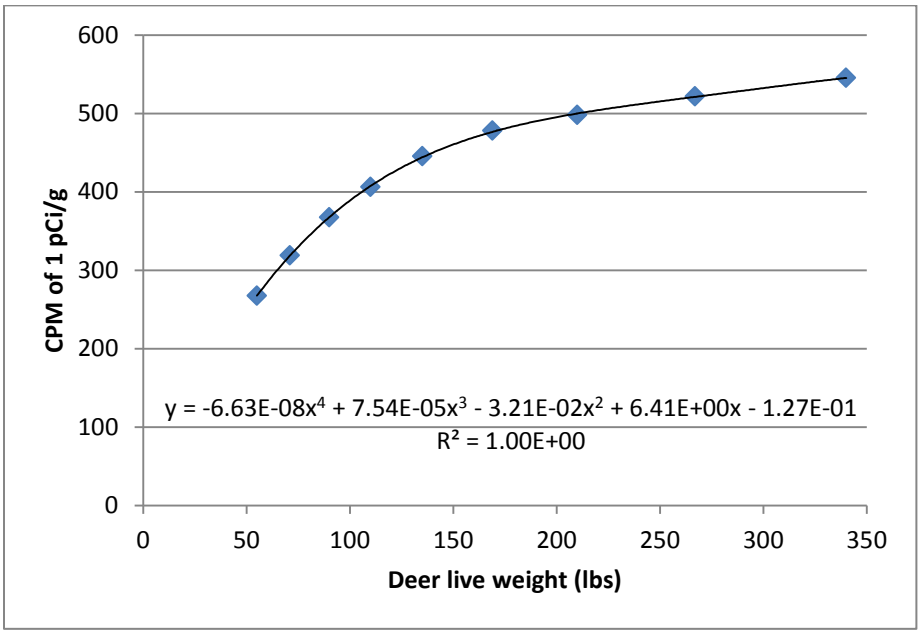

Figure 5-7. Relation of DEER live weight and CPM of 1pCi/g activity.

Table 5-1. Relation of live weight and animal type to activity.

Animal	Live Weight Range	X^4	X^3	X^2	X^1	X^0
Deer	55 – 340	-6.63e-8	7.54e-5	-3.21e-2	6.41e0	-1.27e-1
Hog	49 – 293	-1.08e-7	8.89e-5	-2.88e-2	5.17e0	7.15e1
Turkey	11 – 40	-2.14e-4	2.02e-2	-8.26e-1	2.38e-1	2.90e1
Coyote	25 – 135	1.20e-6	-3.88-4	3.04e-2	2.71e00	8.12e1

To calculate the modeled CPM for a live deer with weight W, the equation would look like:

$$\frac{CPM_{modeled}}{1\ pCi/g} = -6.63 \times 10^{-8}W^4 + 7.54 \times 10^{-5}W^3 + -3.21 \times 10^{-2}W^2 + 6.41W + -1.27 \times 10^{-1}$$

If the dressed weight of an animal is entered into the system, the system converts the dressed weight to the expected live weight using an appropriate polynomial obtained from (OKDOA, 2008) (PSU, 2016) (Miller, 1968) (WSU, 2013).

If an animal's weight is outside of the modeled weight range, the user is prompted to verify the input is correct and if confirmed, the predicted activity is calculated using a linear extrapolation of the curve using the two smallest or two largest modeled weights.

For example, if a Deer weighed 400 lbs the modeled CPM would be calculated at both 267 and 340 lbs and then extrapolated to 400 lbs through the equation:

$$CPM_{400} = \mathrm{CPM}_{267} + \frac{400 - 267}{340 - 267} * (CPM_{340} - CPM_{267})$$

The concentration of the Cs-137 in the whole animal (in pCi/g) is then:

$$Conc_{animal} = \frac{CPM_{measured}}{\left(\frac{CPM_{modeled}}{1\frac{pCi}{g}}\right)}$$

A complete description of these models is found in SRNL-STI-2017-00293 (Brand, 2017).

5.7 Concentration in Animal to Concentration in Meat

The Cs-137 in an animal could be distributed in several different ways. It could be evenly distributed throughout the whole animal, it could be concentrated solely in the meat, or it could be located in the parts of the animal with an abundance of sodium and potassium. The reported dose is calculated from the concentration in the meat. The accuracy of the HDTS is judged by comparing laboratory reported activity to the field reported activity and we expect the slope of this comparison to be close to 1.0.

5.7.1 Cs-137 is evenly distributed

If the Cs-137 is evenly distributed throughout an animal, $Conc_{meat}=Conc_{animal}$ as calculated in the previous section. As shown in Figure 5-8, this is clearly not the case (since $y \neq 1x$). If the 2016 field measurements were made using this model, they would underreport, by 23% (whole) and 32% (dressed), the activity in the meat of the animals. This is the model used by the original HDTS during the two Fall Forestry hunts of 2016. Upon reviewing the data, it was determined that this model under reported the activity in the meat. A correction factor was applied to distribute the Cs-137 only into the meat after which, only one animal from those hunts had activity that contributed to dose (and that was less than 0.8 mrem).

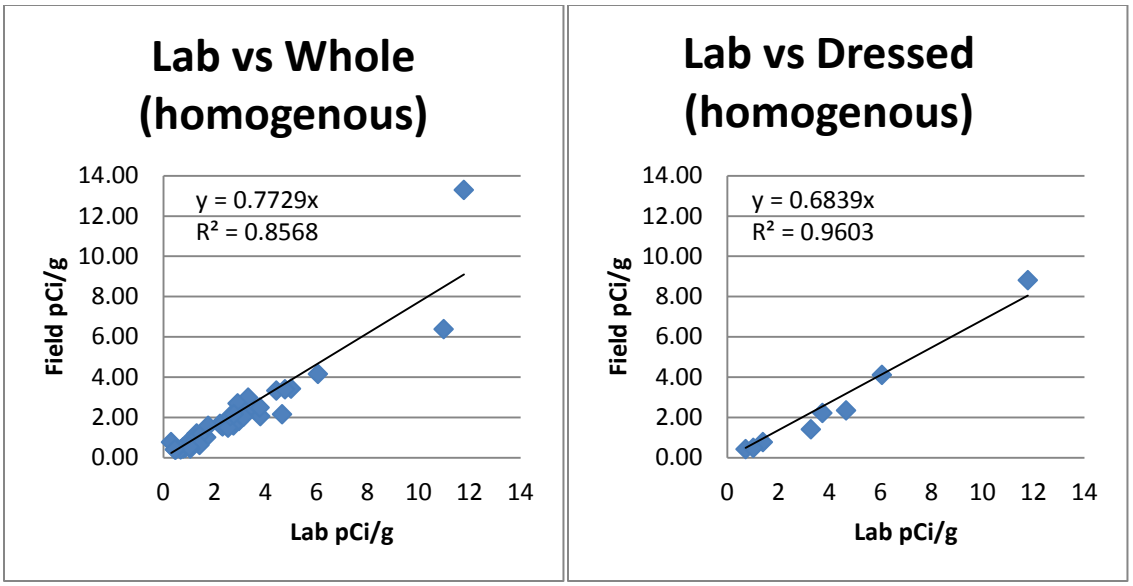

Figure 5-8. Lab vs field measured activity in pCi/g, field measurements assume Cs-137 is homogenously distributed through the animal.

5.7.2 Cs-137 is 100% in the meat

In this model, used in the regular hunts of the fall of 2016, it was assumed that 100% of the Cs-137 was located in the edible meat of the animal. Each animal was assigned an "EdibleMeat" factor, which was approximately the fraction of edible meat in a live animal. The factors for the various animals were DEER (0.45), HOG (0.57), COYOTE (0.5), and TURKEY (0.5) and the equation calculating the Cs-137 concentration $Conc_{meat}$ was expressed as

$$Conc_{meat} = \frac{Conc_{animal}}{EdibleMeat}$$

While this is the most conservative approach, this had the impact of nearly doubling the reported meat concentration for the harvested animals and producing field reported concentrations between 71% and 51% higher than measured by the lab as shown in Figure 5-9.

This difference was much larger than 1) our measurement uncertainty and 2) the results from the prototype system (which measured dressed and whole animals) would have predicted. We knew some portion of the Cs-137 was in the guts, leading us to our next model.

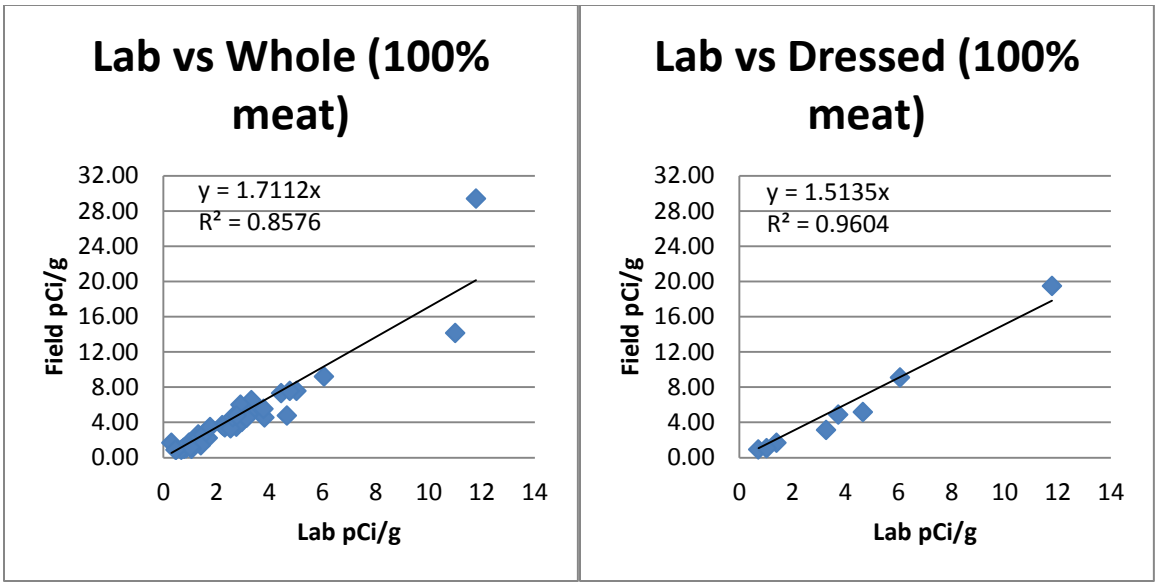

Figure 5-9. Lab vs field measured activity in pCi/g; field measurements assume Cs-137 is located only in the meat.

5.7.3 Cs-137 replaces the sodium and potassium

In a whole deer, approximately 45% of the animal is edible meat, 8% is hide, 13% is bone, 23% is guts, 5% is blood, and 6% is non-edible meat as shown in Figure 5-10 and documented in (Schmidt, 2000). Upon ingestion, Cs-137 preferentially partitions to locations with an abundance of sodium and potassium, which are mostly the blood, guts, edible meat, and non-edible meat (5%, 23%, 45%, and 6%, respectively, for a total of 79%).

A dressed deer is 72% of the whole deer (edible meat, hide, bone, and non-edible meat) and the Cs-137 containing portions are the edible meat and non-edible meat (45% and 6% = 51%). Therefore, the portion of a dressed deer with Cs-137 is 51%/72% = 71%.

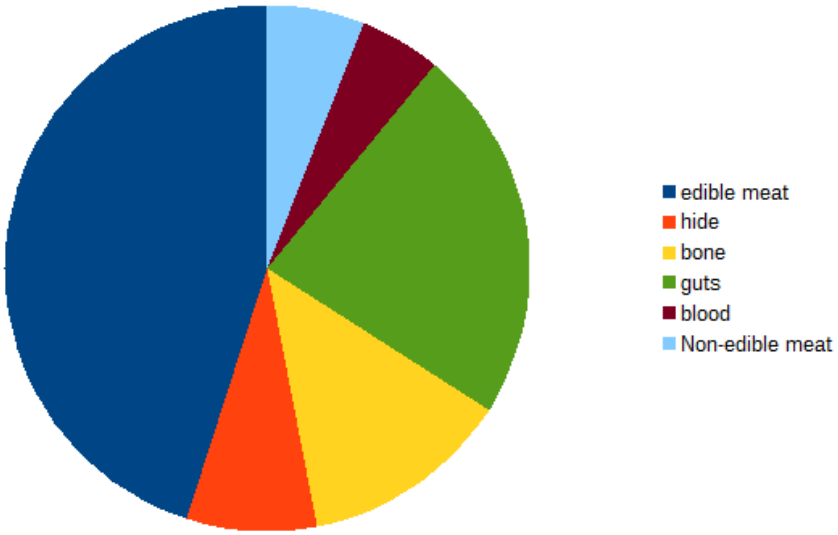

Figure 5-10. Whole deer composition.

We are calling this relationship (79% - whole and 71% - dressed) the Biological Correction Factor (BCF). After we measure a deer and determine the concentration of Cs-137 in the whole animal (live or dressed weight) we can use the appropriate BCF to calculate the concentration of Cs-137 in the meat as:

$$Conc_{meat} = \frac{Conc_{animal}}{BCF}$$

This concentration matches very well with the lab measurements, as shown in Figure 5-11. The combination of MCNP and BCF models causes a reported activity bias of -2% and -4% (whole and dressed) below the laboratory measurement. The average model bias (-3%) is incorporated as a part of the measurement uncertainty.

For the other harvested animals (HOG, TURKEY, COYOTE) this Biological Correction Factor needs to be determined and experimentally validated. Currently, for these animals the BCF is set to the Edible Meat factor, which will over-report the activity in these animals.

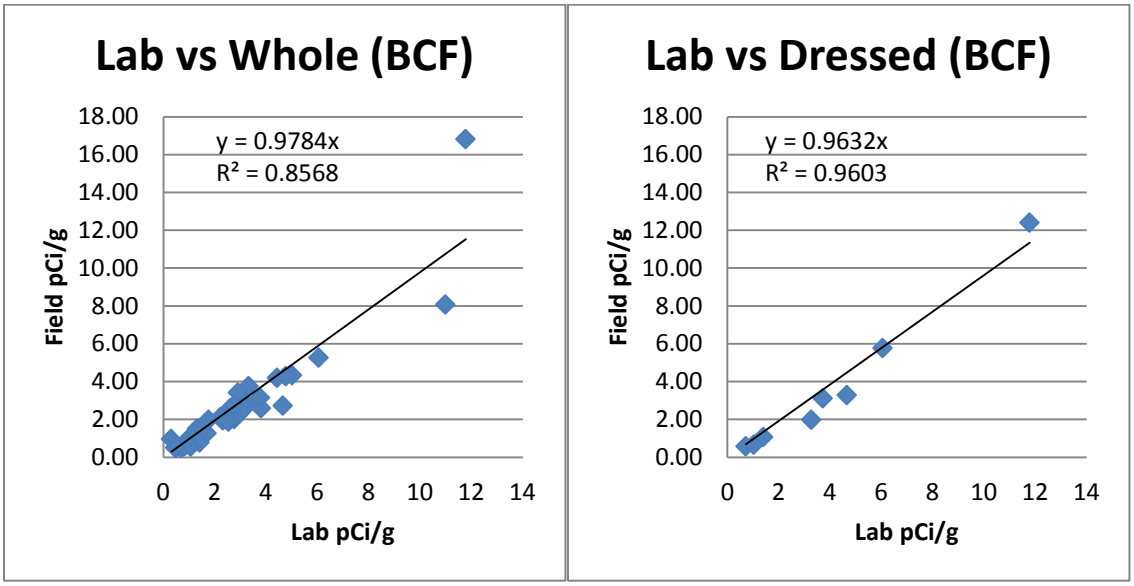

Figure 5-11. Lab vs field in pCi/g; the field measurements assume the Cs-137 is co-located with sodium and potassium.

5.8 Measurement Uncertainty

The percent uncertainty in the activity of the animal is determined during each measurement. This uncertainty accounts for the counting statistics, placement of the animal on the system, gain shift in the detector, and the uncertainty in the counts-to-activity models. Each uncertainty is independent; therefore the total uncertainty is calculated in quadrature (Equation 5-1). An average QC phantom will have a measurement uncertainty of 7%, an animal with average activity will have a measurement uncertainty of 17%, and an animal in a worst-case scenario (low activity, high drift) will have a measurement uncertainty of 33%, as shown in Table 5-2.

$$\sigma_{total} = \sqrt{\sigma^2_{counting\_stats} + \sigma^2_{placement} + \sigma^2_{drift} + \sigma^2_{model}}$$

Equation 5-1. Total uncertainty.

Table 5-2. Uncertainty contributions.

	QC Phantom		Deer	
			activity near MDA	average activity
	worst case	typical	worst case	typical
Counting Stats	5%	5%	30%	17%
Placement	2.50%	2.50%	3%	3%
Drift	12%	0%	12%	0%
Model Bias	-3%	-3%	-3%	-3%
Total Uncertainty	**14%**	**6%**	**33%**	**17%**

5.8.1 Counting Statistics

The percent uncertainty in the recorded counts is based on the Poisson distribution, and is calculated as described in (Knoll, 2000):

$$\sigma_{counting\_stats} = \frac{\sqrt{Left_{Cs} + ROI_{Cs} + Right_{Cs} + Left_{Bkg} + ROI_{Bkg} + Right_{Bkg}}}{Net_{Cs} - Net_{Bkg}} * 100$$

Equation 5-2. Counting Statistics Uncertainty.

Where the ROI_{Bkg} (and ROI_{Cs}) is the total number of counts in the ROI measured during the background (and animal) count and the Net_{Bkg} (and Net_{Cs}) is the number of counts in the ROI less the sum of the counts in the regions to the left and right of the ROI measured during the background (and animal) count. This results in an uncertainty between 6000% for samples near background, 30% near MDA, and 5% for samples with the activity of the phantom.

5.8.2 Placement

The percent uncertainty of animal placement was determined by counting the deer with the most radioactivity (see section 9.0), twelve times. After each measurement the animal was removed from the detector system and replaced before the next measurement. This resulted in the total CPM uncertainty as

$$\sigma_{total} = \frac{\sigma_{CPM}}{\mu_{CPM}} * 100 = 0.034 * 100 = 3.4\%$$

Where σ_{CPM} is the standard deviation of the measurements and μ_{CPM} is the mean CPM measurement. To calculate placement uncertainty, the following values were used in Equation 5-1 :$\sigma_{total} = 3.4\%$, $\sigma_{counting\_stats} = 2.4\%$, $\sigma_{drift} = 0\%$, $\sigma_{model} = 0\%$. The counting statistics uncertainty of 2.4% was calculated using the measured data and Equation 5-2. The detector did not drift during the measurements and the placement uncertainty is based only on recorded CPM, so there is no model uncertainty. This calculation results in $\sigma_{placement} = 2.5\%$.

5.8.3 Drift

The uncertainty in the CPM is also impacted by any gain shift in the detector. This is accounted for by relating how a percent change in the Eu-155 value from the calibrated Eu-155 value translates into a percent change in the reported Cs-137 CPM value, as shown in Figure 5-6. This equation is of the form

$$\sigma_{drift} = 10.641 * Eu^2 + 0.958 * Eu$$

Where Eu is the percent change in Eu CPM. For typical measurements this uncertainty is less than 1%. We have hard-coded a limit of 7% Eu-155 change, which corresponds to a maximum change in Cs-137 CPM (σ_{drift}) of 12%. If this Eu-155 value is exceeded the system will prompt the user to recalibrate the system.

5.8.4 Model Bias

As described in section 5.7.3, the average model bias is -3%.

5.9 Received DOE Dose from Consuming Animal Meat

The received DOE dose for consuming an animal is calculated from the portion of activity attributed to DOE sources ($Activity_{DOE}$). $Activity_{DOE}$ is calculated by subtracting from the total activity ($Activity_{Total}$), which is the calculated $Conc_{meat}$, the background ($Activity_{nonDOE}$).

$$Activity_{DOE} = Activity_{Total} - Activity_{nonDOE}$$

The background activity is defined as the concentration in the animal's meat from Cs-137 that did not originate from the US Department of Energy. This background activity is mostly from above-ground nuclear tests performed in the 1950's and early 1960's by foreign nations and US Department of Defense. For all animals, this non-DOE background is currently set to the decay corrected value of 2.59 pCi/g, as measured on January 1, 2013, and reported in reference (Gaines & Novak, 2016). Section 7.1 has further discussion on this value.

If the activity (after background subtraction) is greater than zero, the received DOE dose is calculated as:

$$Dose_{DOE} = Activity_{DOE} * EdibleMeat * IngestionDose * UnitConversion$$

Where:

- *EdibleMeat* is a polynomial relating an animal's live weight (lbs) to Edible Meat. The recommended conversion to Edible Meat from Live Weight for each Animal Type is as follows:

Deer Edible_Meat (lbs) = 0.4458 * Live_Weight (lbs) + 0.6304
Hog Edible_Meat (lbs) = 0.5700 * Live_Weight (lbs)
Turkey Edible_Meat (lbs) = 0.5113 * Live_Weight (lbs) – 0.0132
Coyote Edible_Meat (lbs) = 0.4700 * Live_Weight (lbs)

These values were obtained based on the following references (OKDOA, 2008) (PSU, 2016) (Brake, Havenstein, Ferket, Rives, & Giesbrecht, 1994) (Ashley, 2002)

- *IngestionDose* is calculated from the EffectiveDoseEquivalent (1.36E-8 Sv/Bq) and ActivityToDose (3.70E9 mrem/uCi) as described in (DOE, 2011) (EPA, 1988).
- UnitConversion is 453.592 g/lbs * 1E-6 uCi/pCi

This received DOE dose is stored in the database and associated with the hunter. For each subsequent animal the hunter receives, this value is included in their annual and lifetime doses, for comparison to the limit values.

6.0 Comparison of the performance of the three systems

Figure 6-1 compares measurements made with the original system (blue), the prototype system (red), and the production system (magenta – whole animals and yellow – dressed animals) to laboratory measurements. The results from the prototype are consistent with the original system but with a lower MDA (1.2 pCi/g) and higher precision.

The dressed animals measured by the HDTS system (yellow circles) performed well because being dressed removed most Cs-137 from the non-meat portion of the animal. A complete description of this effect is found in the Biological Concentration Factor section.

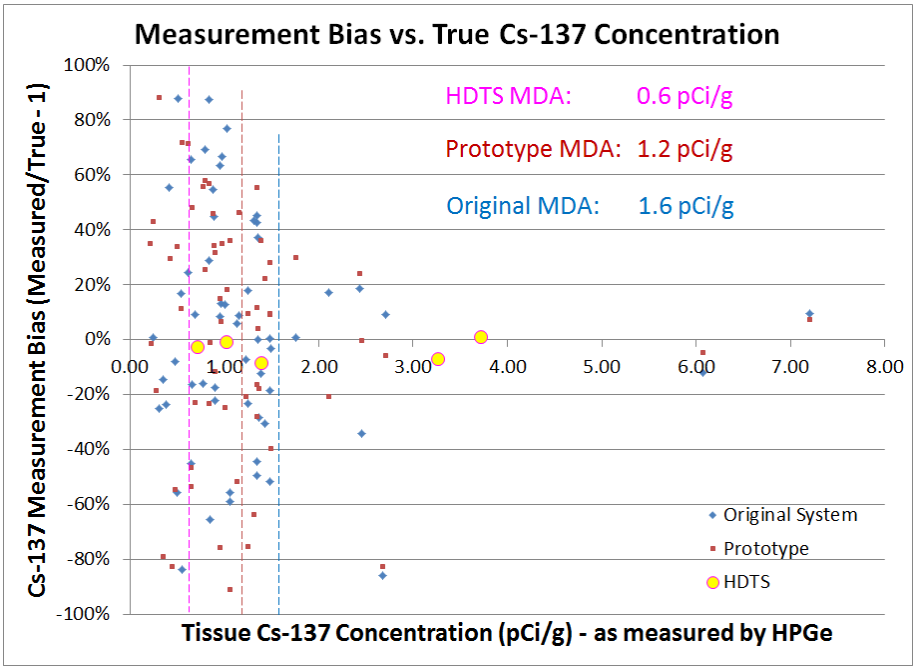

Figure 6-1. Comparison of the HDTS, prototype, and original system minimum detectable activity and precision.

7.0 Recommendations for Method Improvement

7.1 Cs-137 non-DOE Activity in Animals

A report analyzing Cs-137 activity in deer meat obtained from local, off-Site locations (Ft. Gordon, Ft. Stewart, and Ft. Jackson) concludes the background Cs-137 activity is 3.27 pCi/g in Ft. Gordon deer and recommends this number be used as the background Cs-137 concentration for deer harvested at SRS (Shine, 2012). This number is defined as "the one-sided upper tolerance limit with 95% coverage and 95% confidence plus an additional 0.2 pCi/g because the level of Cs-137 is about that much higher than the overall mean on the left size of the plot in Exhibit 2", of Ft. Gordon deer in 2006 (Shine, 2012).

In the fall of 2016, 3.25 pCi/g was used as the Cs-137 non-DOE background concentration subtracted from all harvested animals in the HDTS 2016.0 program based on the report (Jannik G. T., 2016). The 3.25 pCi/g value in that report references the earlier Shine report and was intentionally rounded down to that value.

In the spring of 2017, 2.59 pCi/g decay corrected from January 1, 2013 was used as the Cs-137 background concentration subtracted from all harvested animals. This value is the upper 95% confidence limit of the Cs-137 concentration in the SRS deer herd as measured between 2011 and 2015, reported in (Gaines & Novak, 2016). We are decay correcting from January 1, 2013 as that is the middle of the time period 2011-2015.

To be conservative in our reporting of dose, for the Cs-137 non-DOE background concentration we recommend this value should be either

- 1.80 pCi/g (the mean Ft. Gordon activity, reported on July 1, 2006) (Shine, 2012)
- 1.32 pCi/g (the mean SRS non-contaminated area activity, reported on January 1, 2013) (Gaines & Novak, 2016)
- 1.55 pCi/g (the lower 95% confidence limit (LCL) of the Ft. Gordon deer, reported on July 1, 2006) (Shine, 2012)
- 1.28 pCi/g (the LCL 95 of the SRS deer in non-contaminated areas, reported on January 1, 2013) (Gaines & Novak, 2016)
- 0.00 pCi/g (the most conservative, assuming all Cs-137 at SRS is due to DOE activities)

In any case the background value should be decay corrected from the reported to the present day per the following:

$$Bkg_{now} = Bkg_{then} e^{-(\Delta t * \frac{ln2}{t_{1/2}})}$$

Where Δt is years between then and now (approx. 11 for 2006, and 4 for 2013, and $t_{1/2}$ is the half-life of Cs-137 (30.07 years).

A comparison of the results from implementing the above decay corrected background values in the 2016 hunt, and using the BCF method to determine Cs-137 concentration in the meat is shown in Table 7-1. As shown, using even the most conservative value would have led to reporting only one more animal and dose.

The currently utilized background value (decay corrected 2.59 pCi/g) is appropriate only for deer. If a background value is to be utilized, each animal type harvested at SRS should have this value measured in local, off-Site locations. Based on the data from on-Site harvested animals, there is very little measured Cs-137 in hogs, turkeys, or coyotes so subtracting the deer background is likely to misrepresent the dose received by consuming the meat from these animals.

Table 7-1. Comparison of reportable values utilizing different background values.

Bkg_{then} pCi/g	**Bkg_{now} pCi/g**	**Number of Animals Causing Dose > 10 mrem**	**Max Dose(s) mrem**
3.25	3.25	1	12.29*
2.59	2.01	1	13.53
1.80	1.40	1	14.14
1.32	1.20	1	14.34
1.55	1.21	1	14.33
1.28	1.17	1	14.37
0.00	0.00	2	15.54, 10.46

***Using the method of concentrating all of the Cs-137 into the meat, as done in 2016, this value would be 22.87 mrem. See "Retained Deer" section.**

7.2 Adding Hunters to the System

We recommend keeping the flow of information consistent and in one direction: Measure and record information in the field, copy the data from field computer to office computer for analysis and backup. To that end, hunters should be added to the system in the field. This way the data in the field computer is only updated in the field. In addition, hunters must typically be added to the system anyway, due to transcription errors and substitutions, so this will not be extra burdensome. We estimate it takes less than 30 seconds to add a new hunter into the system in the field.

However, this means the same computer should be used each time. If an alternate computer is used, its database must be updated prior to the hunt.

7.3 Sampling method improvements

7.3.1 Data input

Entering the data into the system is one of the major time consuming and error prone aspects of conducting the hunt, primarily due to poor handwriting. Both the time and errors could be reduced by two simple improvements: preprint and barcode the animal tags. Have the animal

tags preprinted and distributed to the hunters during the pre-hunt briefing. This tag will include the hunter's ID, the hunt compartment, and the hunt stand. This information will be printed as a barcode on the hunt tag, which the field tech entering the information into the system will be able to scan and automatically input. Then the only information required for input by the technician will be the type of animal, weight, and weight type (live or dressed).

7.3.2 Minimum animal weight

For the first twenty deer or hogs, every fifth animal is sampled in the field for confirmatory laboratory analyses. After the twentieth animal, every tenth animal is selected for these analyses. These animals must weigh at least 60 lbs in order to provide adequate meat for these analyses. The software has been designed to skip those animals not meeting these requirements and to automatically alert the field personnel when to sample an animal.

7.3.3 Sample weight

It is suggested that a more accurate system for sample weight determination and utilization during analysis be implemented.

Prior to 11/7/2015, harvested animals were typically measured at EBL using the Geometry 2 standard, a 200 mL solid in a 500 mL LDPE Silgan bottle. The value of 200 g was used as the meat weight. There were no reported deviations from this 200g.

From 11/7/2015 to 12/4/2015, the Geometry 5 standard, a 500 mL solid in a 500 mL LDPE Silgan bottle, was used as the standard. The majority of these 52 samples used a value of 400 g, with a mean value of 395.66 g and a standard deviation of 22.20 g.

From 3/4/2016 – 12/3/2016 the Geometry 5 standard was still in use, but the mean sample weight increased to 460.25 g, with a median value of 469.70 g, and a standard deviation of 35.23 g.

Assuming the sample weights from 3/4/2016 – 12/3/2016 are representative of similar weights in the past, a difference in laboratory reported concentration vs actual concentration value could differ up to 7.7% (35.23 / 460.25).

In order to get the correct sample weight, we recommend recording the actual weight of the bottles before and after filling, not using a tared weight, and calculating the sample weight in the field. This will ensure an adequate and accurate sample mass is obtained.

7.3.4 Sample bottles

During one of the last hunts of 2016, it was noted that the sample bottles were not homogenous; one batch appeared to be HDPE plastic and the other, from a different vendor, either LDPE plastic or thinner construction. The difference in weight between the two bottles is approximately 10 g.

Typically during the hunts, the weight of the empty bottle is not recorded, only the total weight is recorded. So, if the total weight is subtracted from a lower "batch weight", the reported Cs-137

concentration will be lower than it actually is, leading to an approximately 3% error in the reported activity ((2.35-2.29)/2.35 = 3%). We recommend recording both the total weight and the empty weight of the bottle being used.

Examples of each approach are provided below, indicating possible impacts from the assumed initial weigh of the empty bottle.
Actual bottle weighs 60g; assumed bottle weight is 50g (batch weight); 800pCi activity
400g full bottle + Xg sample wt – 50g bottle wt = 350 g sample wt
Reported = 2.29 pCi/g

versus

Actual bottle weight = 60g; 800pCi activity
400g full bottle + Xg sample wt – 60g bottle wt = 340 g sample wt
Reported = 2.35 pCi/g

7.4 HDTS procedure (processing order)

Based on our experience with the system and the observation of the large variability in activity in measuring whole animals, we recommend changing the processing order of the animals.

Current Order:
Harvest->Weigh->Measure Activity-> Calculate and Assign Dose-> (Release or Retain) -> Gut Animal

Recommended Order:
Harvest->Weigh->Quick Scan->(Next Step or Retain)->Gut->Measure Activity -> Calculate and Assign Dose->(Release or Retain)

Introducing a scanning system and gutting prior to measuring the activity would:

1. Limit handling of any contaminated animals
2. Improve the accuracy of dose assigned to the consumer

The scanning system would be a simplified system, with an approximate 5-second count time, where the animal is dragged across the spare HDTS hardware with a “scan” option added to the software, so no additional hardware cost would be incurred. The only input required to use the system would be the animal type and live weight, and even these could likely be simplified to use average values. The output would be an indicator of whether to release or retain the animal based on the calculated maximum possible ingestion dose. If an animal had enough activity to reach this limit, it will be able to be measured during the scan.

The document SRNL-L3200-2016-00141 (Stagich & Jannik, 2016) details the expected dose from handling contaminated animals and concludes that it is not a concern.

The variability in the measured activity in gutted versus whole animals widely differs, as shown by the difference in the R^2 values in Figure 5-11. This is because approximately 25% the activity

in animals is in their blood and guts. By dressing the animal, this variability is decreased and a more accurate assignment of dose received from consuming the meat is possible.

If this proposed change in processing order is accepted, the Dressed Weight of the animal (as documented below), with the exception of Turkeys and Coyotes (which are not dressed) will be used to calculate the activity provided by the MCNP model.

Dressed Weight can be calculated as follows:

Deer Dressed_Weight (lbs) = 0.823 * Live_Weight (lbs) – 5.102
Hog Dressed_Weight (lbs) = 0.720 * Live_Weight (lbs)

The Edible Meat as described in section 5.9 will be used to calculate dose from the activity.

7.5 Retire some phantoms

The SRNS Sample Data Management organization has a series of seven certified phantoms, manufactured by Analytics, a division of Eckert & Ziegler, in Atlanta, Georgia. A summary of these sources and their decay corrected values is presented in Table 7-2. Note the half-life time for Piglet is slightly different. This is because the half-life reported on the certificate is reported in days, as 1.099E+04, which corresponds to 3.009E+01 years and differs from the other reported half-lives.

In order to verify the performance of the HDTS hardware, the detector system measured each phantom at least five times and calculated the average activity and standard deviation of each. This was done by placing the phantoms carefully in the center of the marked location on the detector system and counting for one minute. The average activity values were compared to the decay corrected certificate values and found to be within the certificate reported uncertainty (3.3%) for phantoms Priscilla (2.4%), Miss Piggy (2.6%), and Napoleon (3.0%). For Porky, the difference (4.0%) was minimal. However, for phantoms Piglet (16.0%), Arnold (10.20%), and Wilbur (12.95%) the difference was greater than expected.

To ensure the detector system was performing as expected, these phantoms were re-measured using a small 2x2 NaI detector on the top and bottom of each phantom for one minute and the ratio of counts per minute between the top and the bottom was plotted versus the decay corrected certificate value for disintegrations per second, as shown in Figure 7-1. It was expected this ratio would be a little higher than 1 (due to the plastic being on the bottom of the container) for all the phantoms, since these are homogenous standards. As seen, the top/bottom ratios for Piglet, Arnold, Wilbur, and Napoleon (2000, 30000, 60000, 120000 in the Figure) are significantly below 1.0.

The error bars on the blue diamonds are the normalized Poisson counting statistics as measured at the top of the phantom; these are calculated using Equation 5-2.

We believe the reason the ratios are less than 1 for Arnold, Wilbur, and Napoleon is the possibility these standards were not well mixed when they were created and/or settling occurred during their creation, causing more Cs-137 to be on the bottom of the standard. For Arnold and

Wilbur this is observed in the consistently measured higher-than-stated pCi/g activity and is not observed in Napoleon. One reason Napoleon's measured value could be close to the certificate value but has a different ratio is that some of the resin was added to the standard first, then the activity, then the remainder of the resin. This would cause the ratio to differ from 1, but would allow the measured and certificate values to be close to each other.

Piglet is a different case. It was created 8 years later, the resin is visibly a different color (red vs clear), and the standard itself weighs 13 lbs more than the others. However, the carboy is the same size and the volume of resin appears to be the same (20 L). If the density of the resin is actually 1.444 g/cc versus the reported 1.15 g/cc, the decay corrected activity is 1.94 pCi/g. We would then report the difference in measured vs certificate value as 16.01% (compared to -7.38% originally), which corresponds well with Wilbur's and Arnold's higher activity value.

The 1.444 g/cc value is calculated as follows:
75 lb Piglet – 62 lb (all other Phantoms) = 13 lbs
13 lbs / 20L * 1 L / 1000 cc * 453.6 g / 1 lbs = 0.294 g / cc
Reported density = 1.15, new density = 1.15 g/cc + 0.294 g/cc = 1.444 g/cc

The conversion of decays per second (DPS) to pCi/g is dependent on the density of the resin and if the standards are not homogenous, the ratio of top to bottom will not be approximately 1 and if the activity is at the bottom of the standard, the measured pCi/g will be greater than the certificate values.

Based on the above analysis, we recommend retiring the Piglet, Arnold, Wilbur, and Napoleon standards.

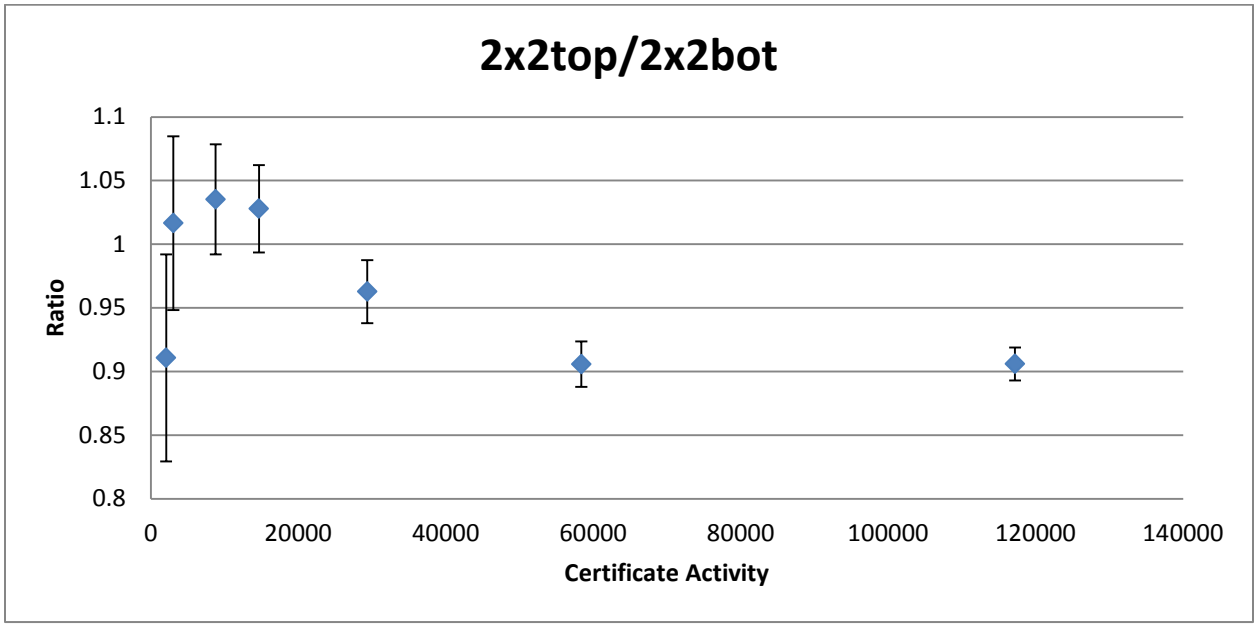

Figure 7-1. Ratio vs Certificate Activity.

Table 7-2. Certificate information for Phantoms.

cert num	name	geometry	weight (lbs)	volume (L)	density (g/cc)	half-life (years)	activity (dps)	calib date	activity (pCi/g)	Years Past	corrected activity (pCi/g)	corrected dps
97791	Piglet	20 L solid in 50 L LDPE Bottle	74	20	1.15	3.009E+01	2.192E+03	8/29/2014	2.576	2.51	2.43E+00	2.069E+03
73020-147	Priscilla II	20 L solid in 50 L LDPE Bottle	62	20	1.15	3.007E+01	3.893E+03	7/14/2006	4.575	10.63	3.58E+00	3.047E+03
73021-147	Miss Piggy II	20 L solid in 50 L LDPE Bottle	62	20	1.15	3.007E+01	1.123E+04	7/14/2006	13.196	10.63	1.03E+01	8.789E+03
73022-147	Porky Jr	20 L solid in 50 L LDPE Bottle	62	20	1.15	3.007E+01	1.873E+04	7/14/2006	22.009	10.63	1.72E+01	1.466E+04
73023-147	Arnold Jr	20 L solid in 50 L LDPE Bottle	62	20	1.15	3.007E+01	3.750E+04	7/14/2006	44.066	10.63	3.45E+01	2.935E+04
73024-147	Wilbur Jr	20 L solid in 50 L LDPE Bottle	62	20	1.15	3.007E+01	7.459E+04	7/14/2006	87.650	10.63	6.86E+01	5.838E+04
73025-147	Napoleon Jr	20 L solid in 50 L LDPE Bottle	62	20	1.15	3.007E+01	1.498E+05	7/14/2006	176.028	10.63	1.38E+02	1.172E+05
73038-147	Button Source	1 in dia x 0.25 in thick button				3.007E+01	5.150E+04	7/14/2006		10.63		4.030E+04
	corrected Piglet	20 L solid in 50 L LDPE Bottle	74	20	1.444	3.009E+01	2.192E+03	8/29/2014	2.051	2.51	1.94E+00	2.069E+03

8.0 Production System (HDTS) – Improvements

The fall 2016 hunts were really an extended field trial in order to test the full capabilities of the system and to ensure the system would meet the long-term needs of the customer. As such, a few needs were identified and were addressed to improve the system and ensure adequate performance.

- Two detectors were integrated into the system, such that both detectors can be controlled from one computer
- The Lexan cover and box was modified such that the cover can only be oriented in 1 direction.
    - This was noted to be needed after observing a step-change in the measured CPM of the phantoms from 1500 to 1200 and then back to 1500. This error did not impact any field measurements using the backward plate, because the SRNL technical lead noted the issue and marked on the plate the correct placement of the deer.
- The data storage system was transitioned to a Microsoft Access database.
- Incorporated the recommendation on Background Subtraction (use a decay corrected value) and Calculation of Activity (use the BCF method).
- Radio buttons were placed next to the weight input, labeled Live Weight and Dressed Weight. The current default is to Live Weight.
    - The majority of animals come from the field whole (live weight), however occasionally they come in as dressed, so this is needed to properly report activity, which is based on live weight.
    - The default could be changed to Dressed Weight as needed.

9.0 Fall 2016 Retained Deer

9.1 Reported Activity

In the fall of 2016, one harvested animal was retained due to reported activity that would have caused excessive dose. The "retained deer" did not actually have enough activity to cause excessive dose. It was retained because we were using the method of concentrating all of the Cs-137 into the meat, resulting in reporting 27.3 pCi/g activity (22.9 mrem reported dose). If we had used the BCF method on the whole deer, we would have reported 15.5 pCi/g activity (13.5 mrem). During a special analysis of the retained deer, we measured the deer when it was whole and dressed and the average measurement was 16.8 pCi/g (14.8 mrem) and 12.4 pCi/g (10.4 mrem), respectively. These respective values differ by 30% and 5% from the reported lab measurement of 11.8 pCi/g.

This example shows why we recommend dressing the deer prior to measuring activity.

9.2 Laboratory Analysis of Retained Deer

We will address the lab results of the retained deer in a separate report.

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