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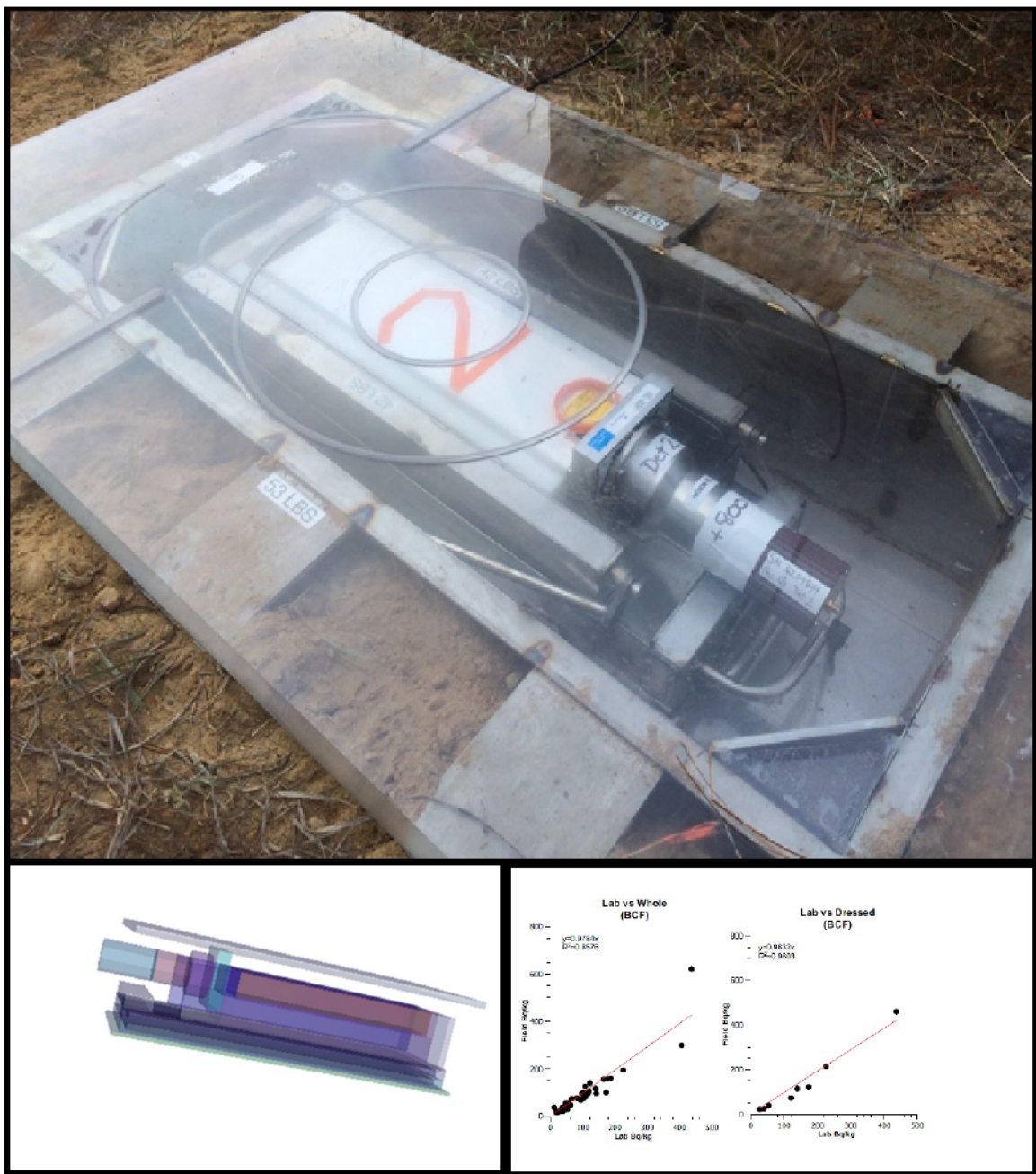
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## Graphical Abstract

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# Highlights

## Improved field-portable system to measure Cs-137 in wildlife

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- Using a MCNP-derived algorithm and a large, shielded detector increases accuracy
- An on-board check-source prevents unwanted drift and reduces uncertainty
- Understanding which parts of the body contain Cs-137 increases accuracy

# Improved field-portable system to measure Cs-137 in wildlife

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## Abstract

We have developed an improved system to measure Cs-137 in wildlife at the Savannah River Site. This field-portable system consists of a shielded 5 cm by 10 cm by 40 cm NaI detector controlled by an Ametek Ortec Digibase. Measurement of an animal's radioactivity is made by placing the animal at a predefined location on the detector system for a one minute count-time. The counts, animal type, and animal weight are then used as inputs to an algorithm which calculates the amount of Cs-137 within the whole animal and within the edible meat portion of the animal. The results from these calculations are used to estimate the received dose from eating this animal and is included in the Savannah River Site's Hunter Dose Tracking System. This system has a detection limit of 0.60 pCi/g (22.20 Bq/kg) with a typical measurement uncertainty of less than 0.32 pCi/g (11.84 Bq/kg).

**Keywords:** Cs-137, wildlife monitoring, bioaccumulation, NaI detector

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## 1. Introduction

The Savannah River Site (SRS) is a 777-square-km US Department of Energy (DOE) reservation near Augusta, GA. It has a large population of wildlife, including white-tailed deer (*odocoileus virginianus*), feral pigs (*sus scrofa*), eastern wild turkeys (*meleagris gallopavo silvestris*), and coyotes (*canis latrans*). To properly manage the deer population and to reduce animal-vehicular collisions, the Savannah River Office of DOE, in conjunction with the US Forestry Service, conducts hunts for these animals.

To protect the public health, the DOE operator, Savannah River Nuclear Solutions (SRNS), uses the Hunter Dose Tracking System (HDTS) to measure and record the potential radiation dose received by hunters who consume the meat of animals harvested at SRS. This system ensures those consumers do not receive a dose in excess of the SRNS-specified dose limits of 22 mrem (0.00022 Sv) annually and 360 mrem (0.0036 Sv) over their lifetime. These dose limits were chosen by SRNS to follow DOE order 458.1 sections 4.b.(1).(a), 4.e.(1).(a).3, and 4.e.(1).(c), (DOE, 2011a).

Because it bioaccumulates, Cs-137 is the largest contributor to dose from consuming animals harvested at the Savannah River Site (ATSDR, 2004). 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 edible meat of the animal is determined and the dose is calculated from this concentration. If this value plus any dose received previously is below the dose limits set by the DOE operator (22 mrem (0.00022 Sv)

annual and 360 mrem (0.0036 Sv) lifetime), then the animal is released to the hunter of that animal. The dose from this animal is recorded and associated with that hunter within the HDTS, which tracks the received annual and lifetime dose. If an animal has enough activity that its consumption would create a dose that exceeds either of these thresholds, it is not released to that hunter.

Since the 1960s, when the wildlife management program was first instituted, the average amount of Cs-137 measured in white-tailed deer has decreased from 13 pCi/g (480 Bq/kg) to less than 2 pCi/g (74 Bq/kg) (Gaines and Novak, 2016). This measured activity was approaching the Minimal Detectable Activity (MDA) of the system originally used to measure Cs-137, 1.6 pCi/g (59.2 Bq/kg). To continue to protect the hunters, a system with increased sensitivity was needed.

## 2. Material and Method

To increase the sensitivity of the HDTS, the replacement system is shielded and uses a St. Gobain 5 cm by 10 cm by 40 cm NaI detector coupled to an Ametek Ortec Digibase multi-channel analyzer, which processes the counts and is controlled through a custom software interface.

As shown in Figure 1, a shielded box, intended to be buried, was designed. This reduces the background noise and allows the animals to be easily moved to a defined location relative to the detector. The steel box dimensions are 39 cm wide by 86 cm long by 18 cm high. The eight components of the shielded box consist of the box, detector holder, Lexan cover, encapsulated lead shielding (4 parts), and polyethylene detector supports. Two of the lead shielding components (each 1.27 cm thick) are placed on the bottom and two (each 2.54 cm thick) are placed on either side of the detector holder. The patent (DiPrete et al., 2017) has a complete description of the system. The assembly is covered by a Lexan lid with markings showing where

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Figure 1: Production HDTS shielding and animal placement cover.

to place the calibration source, the small animals, and the large animal haunches. All of the components are labeled for correct orientation, which ensures consistent system setup.

Due to the shielding and larger detector, the improved system has, on average, a 40% lower MDA of 0.60 pCi/g (22.2 Bq/kg) when compared to the original system's 1.6 pCi/g (59.2 Bq/kg). As described by Currie (1968), the MDA is calculated in counts per minute for each measurement:

$$MDA(cpm) = \frac{2.71 + 4.65 \sqrt{(L_{Cs} + I_{bkg} + R_{Cs}) \times Time}}{Time} \quad (1)$$

where  $L_{Cs}$  and  $R_{Cs}$  are the sum of counts in the left and right areas of the sample spectra (see Figure 2) and the  $I_{bkg}$  is the number of counts in the region of interest when no sample is on the system.  $Time$  is the count time in minutes.

The Currie equation for MDA is primarily driven by random uncertainty. It is proportional to  $1/\sqrt{Time}$ . For example, to decrease the MDA by 50%, increase the count time by a factor of four.

### 2.1. 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 high voltage is applied to the detector, it is calibrated by placing a Cs-137 check source over the detector system, in the center circle shown in Figure 1. The system turns on the gain stabilization and acquires data for 30 seconds, which centers the peak at 662 keV. The background in the Cs-137 region of interest is measured by removing the check source, ensuring no sources are near the system, and then making a one minute measurement. This background counts-per-minute value is recorded in the software. The system then measures the quality check (QC) calibration source and calculates its activity.

The QC calibration source is a NIST-traceable 20 L solid in a 50 L low-density polyethylene container with a decay-corrected activity of 3.60 pCi/g (133.20 Bq/kg). The mean difference in twenty field-measured versus decay-corrected certificate activities was -0.070 pCi/g (-2.6 Bq/kg) or -1.9%, with a standard deviation of 0.20 pCi/g (7.4 Bq/kg), 5.5%.

In order to pass the QC, the measured activity must be within 16% of the decay-corrected certificate value. This 16% is three standard deviations of the field-measured calibration source and well below the 25% requirement of SRS QA Procedure 1Q-12-3 (SRNS, 2018). If the measurement of the QC calibration source is outside of this 16% limit, two follow-up QC measurements must pass this check in order to use the instrument. If these checks fail, the system is unable to be used until the cause for failure is identified and corrected.

As part of the system, an Eu-155 check source is placed on the detector during the measurements. The counts-per-minute in the Eu-155 region of interest are saved by the system during the QC calibration source measurement. When measuring the animals, the software compares the counts of Eu-155 measured to this saved value. If these values differ by more than 7%, the system will prompt the user to recalibrate the system using the Cs-137 check source. This control is further described in Section 2.3.

### 2.2. Region of Interest

To determine the amount of Cs-137, a region of interest (ROI) is defined. The recommended ROI size, as described in Canberra Industries (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  $3 \times FWHM/2$  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.

For our measurements, we define two regions of interest. One is for Cs-137 and the other is for the Eu-155 check source. The channels for these sources are determined for each detector system. This is done by operating the detector at the manufacture's recommended high-voltages with a fine-gain adjustment such that the Cs-137 peak falls in channel 331, approximately half of the actual 662 keV of the photon. For one of the detectors, when the Cs-137 peak is at channel 331 the half-max channel is at channel 343. Therefore the region of interest for Cs-137 is from channels 295 – 367 as shown in Figure 2. 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 24 channels wide, between channels 42 – 66. The left and right regions are each 12 channels wide. This allows coverage of both peaks but does not cover any X-ray peaks that may be in the spectra, as shown in Figure 3.

### 2.3. Drift Control

It is well known that NaI detector systems drift due to environmental factors and we observed this drift in our system. Subsequently, we developed drift controls and incorporated those

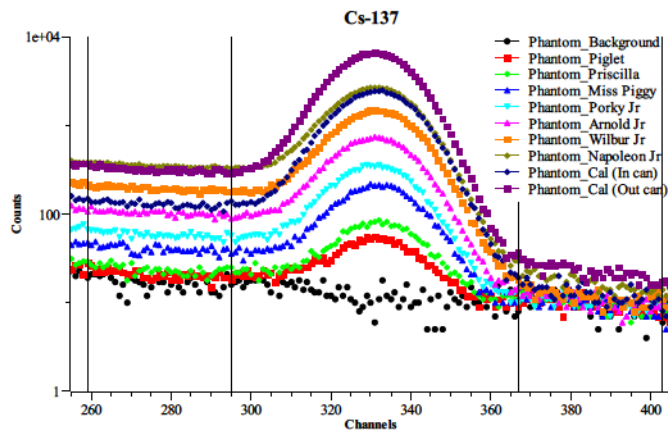


Figure 2: Cs-137 ROI for multiple NIST-traceable sources.

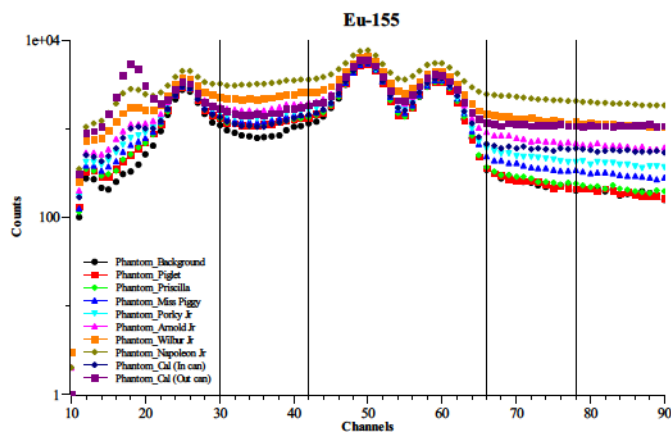


Figure 3: Eu-155 ROI for multiple NIST-traceable sources.

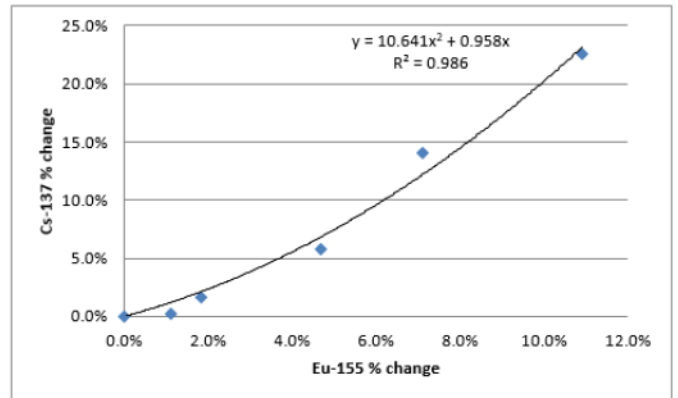


Figure 4: Relating percent change in Eu-155 CPM to percent change in Cs-137 due to gain shift.

into the system. To monitor system drift during the hunts, a Eu-155 source was added to the system. After each animal is assayed, the CPM of the Eu-155 source is compared to the value measured when the QC calibration source 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 and determine when the drift became unacceptable, a calibration source, which had a decay-corrected activity of 16.1 pCi/g (595.7 Bq/kg), was measured by the system for one minute at a series of gain settings and the relationship between the percent change in both the Eu-155 CPM and Cs-137 CPM as a function of gain was developed. The measurement at each gain setting was performed three times. The gain multiplier setting was initially set so the Cs-137 peak was centered at channel 331 at the operating voltage of the detector. The gain multiplier was then decreased in a series of steps from 1.1715 to 0.90.

The relationship between the percent change in the Eu-155 CPM and the Cs-137 CPM is best described by the quadratic best-fit equation, shown in Figure 4. This means a small decrease in the Eu-155 CPM reflects a much larger decrease in the Cs-137 CPM. Figure 4 only reflects the gain decrease between 1.1715 and 1.065, because at this point the Cs-137 CPM measured in the ROI is nearly 25% lower than the actual Cs-137 CPM, well outside the bounds of acceptable error.

We defined the drift limit for the Eu-155 CPM to be 7.0%. This limits the maximum uncertainty of the Cs-137 CPM to be less than 12%. The calculated uncertainty in the Cs-137 CPM is incorporated into the reported measurement uncertainty.

When measuring high levels of Cs-137 radioactivity (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 “Phantom\_Cal (Out can)” line in Figure 3. Further, we saw spectral broadening due to Compton scattering in the calibration source with the most Cs-137. The spectra of all of the calibration sources were examined to determine if either these X-rays or Compton effects would cause the Eu-155 CPM to



ever exceed the 7% limit. None of the calibration sources exceeded this limit, with “Phantom.Napoleon Jr” (which has an activity 600% greater than the release limit) causing the greatest difference in the Eu-155 CPM measurement (6.25%), due to Compton scattering.

#### 2.4. MCNP Model (Counts to Concentration)

The accuracy of the reported activity was increased by constructing a model of the detector and various animals within the MCNP (Monte-Carlo N-Particle) code. MCNP is a general-purpose Monte Carlo N-Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport (LANL, 2013). Our model represents the detector, the shielded box, the animal, and the radiation. In it, the Cs-137 is evenly distributed throughout the animal and the expected number of decays measured by the detector system is computed (Brand, 2017).

For each animal, between six and nine MCNP models, differing in the modeled volume of the animal, were created and run. The deer, pigs, and coyotes were modeled as cylinders, and the turkeys were modeled as spheres. The volume of each animal model was based on the relationship between the chest girth and live weight, as described in Miller (1968); OKDOA (2008); PSU (2016); WSU (2013), and the body density of the animal, which is 1 kg/L. The live weight is the weight of the animal when alive. The predicted counts-per-minute per 1 pCi/g (37 Bq/kg) of Cs-137, as a function of weight, in lbs, was created from these models as a fourth-order polynomial. This equations coefficients are defined in Table 1 and shown in Equation (2).

To calculate the modeled CPM for a deer with a live weight of  $w$  (in the range 55 – 340 lbs), the equation is:

$$\frac{CPM_{modeled}}{1pCi/g} = -6.63E-8 \times w^4 + 7.54E-5 \times w^3 - 3.21E-2 \times w^2 + 6.41 \times w - 1.27E-1 \quad (2)$$

The modeled animal sizes were chosen to represent the range of weights typically seen in harvested animals at SRS (deer, pig, turkey) or when hunted elsewhere (coyotes). If an animal's weight is outside of the modeled weight range, the predicted value is calculated using a linear extrapolation of the curve using either the two smallest or two largest modeled weights. For example, if a deer weighed 400 lbs (181 kg), the modeled CPM would be calculated at both 267 lbs (121 kg) and 340 lbs (154 kg), two of the modeled weights, and then extrapolated to 400 lbs (181 kg) through the equation:

$$CPM_{400} = CPM_{267} + \frac{400 - 267}{340 - 267} \times (CPM_{340} - CPM_{267}) \quad (3)$$

The concentration of Cs-137 in the whole animal (in pCi/g) is determined from the measured CPM ( $CPM_{animal}$ ) and the mod-

eled CPM ( $CPM_{modeled}$ ) by:

$$\frac{CPM_{animal}}{conc_{animal}} = \frac{CPM_{modeled}}{1pCi/g} \quad (4)$$

$$conc_{animal} = \frac{CPM_{animal}}{CPM_{modeled}} \times 1pCi/g \quad (5)$$

#### 2.5. Live versus Dressed Weight

When most animals are brought to the check-stand, the recorded weight is the live weight. However, the deer and pigs are measured for radioactivity after being dressed (the entrails are removed), so the software interface converts the live weight to the dressed weight using a linear equation derived from data reported in OKDOA (2008); PSU (2016); Miller (1968); WSU (2013) with the parameters shown in Table 2. Equation (6) uses those parameters to calculate the dressed weight of a deer (lbs):

$$Deer_{dressed} = 0.823 \times Deer_{live} - 5.102 \quad (6)$$

This dressed weight is used in Equation (2) to calculate the modeled activity in the dressed animals. When used this way, the dressed animal is “smaller” than the whole animal and the reported concentration is 9% less than the whole animal, as shown in Figure 5. However, as discussed in Section 2.7.3, when the correct Biological Correction Factor is applied to the whole and dressed animals, the reported concentration for each matches very well with the laboratory-measured results, Figure 7.

#### 2.6. Laboratory Measurements

As part of the environmental reporting requirements at SRS, a portion of meat, approximately 450 g, from every tenth animal (deer and pigs only) is collected in a 500 mL low-density polyethylene bottle and sent to the laboratory for measurement. These meat samples are assayed on a Canberra HPGe detector for 5000 seconds. From 2006 through 2016, the average amount of Cs-137 detected in these samples was 2.04 pCi/g (75.48 Bq/kg) with an average error of 0.24 pCi/g (8.88 Bq/kg). The maximum amount of Cs-137 measured over this time frame was 17.18 pCi/g (635.66 Bq/kg), recorded in 2007. The average MDA of these samples was 0.06 pCi/g (2.22 Bq/kg) and 34 of the 862 samples had activities less than the MDA.

#### 2.7. Concentration in Animal to Concentration in Meat

The Cs-137 in an animal could be distributed in several different ways: evenly distributed throughout the whole animal, concentrated solely in the meat, or located in the parts of the animal with an abundance of sodium and potassium. The dose is calculated from the amount of Cs-137 in the meat, as measured in the field. The accuracy of the HDTS is judged by comparing the activity of laboratory-measured meat samples to the field-measured activity. Therefore, the model of how Cs-137 is distributed within the animal is the key to the accuracy of this method.

The following comparisons and model development were for deer, future work will expand this method to pigs, coyotes, and turkeys.

Table 1: Parameters to relate live weight (lbs) and animal type to modeled concentration.

Animal	Live Weight Range (lbs)	$w^4$	$w^3$	$w^2$	$w^1$	$w^0$
Deer	55 – 340	-6.63E-8	7.54E-5	-3.21E-2	6.41E+0	-1.27E-1
Pig	49 – 293	-1.08E-7	8.89E-5	-2.88E-2	5.17E+0	7.15E+1
Turkey	11 – 40	-2.14E-4	2.02E-2	-8.26E-1	2.38E-1	2.90E+1
Coyote	25 – 135	-1.20E-6	-3.88E-4	3.04E-2	2.71E+0	8.12E+1

Table 2: Dressed weight (lbs) from live weight (lbs).

Animal	$x^1$	$x^0$
Deer	0.823	-5.102
Pig	0.720	0.000
Turkey	0.817	-0.754
Coyote	1.000	0.000

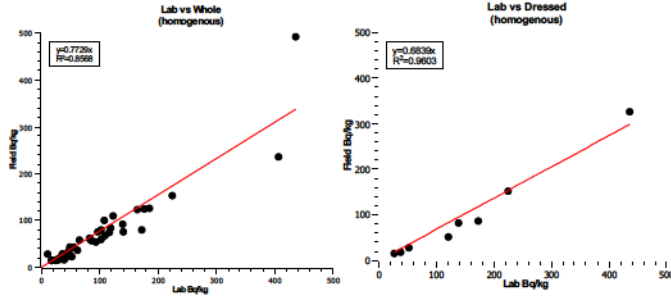


Figure 5: Lab vs field measured activity in Bq/kg. Field measurements assume Cs-137 is homogeneously distributed throughout the deer.

### 2.7.1. Cs-137 is evenly distributed

If the Cs-137 is evenly distributed throughout an animal,  $conc_{meat} = conc_{animal}$ . As shown in Figure 5, this is not the case because the slope is not unity. This model of Cs-137 distribution accounts for 77% and 68% of the activity in the meat of a whole and dressed deer, respectively.

### 2.7.2. Cs-137 is 100% in the meat

After two hunts, we determined the first model of Cs-137 distribution under-reported the activity in the meat. A conservative correction factor was applied to distribute 100% of the Cs-137 into the edible meat, based on Dixon (2012). Each animal type was assigned an Edible Meat factor ( $E$ ), which is the fraction of Edible Meat to Live Weight, and uses the same equations presented in Section 2.9. The equation calculating the Cs-137 concentration  $conc_{meat}$  is then:

$$conc_{meat} = \frac{conc_{animal}}{E} \quad (7)$$

This was the most conservative assumption and produced field-reported concentrations between 71% and 51% higher than measured by the laboratory, as shown in Figure 6.

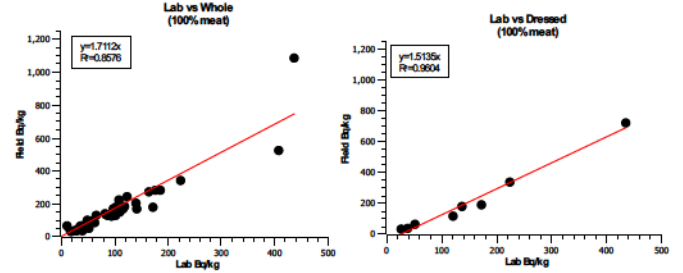


Figure 6: Lab vs field measured activity in Bq/kg. Field measurements assume Cs-137 is located only in the meat.

### 2.7.3. Cs-137 replaces the sodium and potassium

A whole deer, by weight, is approximately 45% edible meat, 8% hide, 13% bone, 23% entrails, 5% blood, and 6% non-edible meat, as documented in Schmidt (2000). Upon ingestion, Cs-137 preferentially partitions to locations with an abundance of sodium and potassium. These parts are mostly the edible meat, entrails, blood, and non-edible meat. By weight, these Cs-137 containing portions are 79% of the whole deer.

A dressed deer is 72% of the whole deer and consists of the edible meat, hide, bone, and non-edible meat fractions. The Cs-137 containing fractions are the edible meat and non-edible meat (45% and 6% = 51%). Therefore, by weight, 51%/72% = 71% of a dressed deer contains Cs-137.

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:

$$conc_{meat} = \frac{conc_{animal}}{BCF} \quad (8)$$

This model of concentration matches very well with the lab measurements, as shown in Figure 7. The combination of MCNP and BCF models causes a reported bias of -2% and -4% (whole and dressed) below the laboratory measurement. The average model bias (-3%) is included in the total measurement uncertainty calculation.

For the other harvested animals (pigs, turkeys, and coyotes) the BCF is set to the Edible Meat factor, which will over-report the activity in these animals. For these animals, the BCF needs to be determined and experimentally validated.



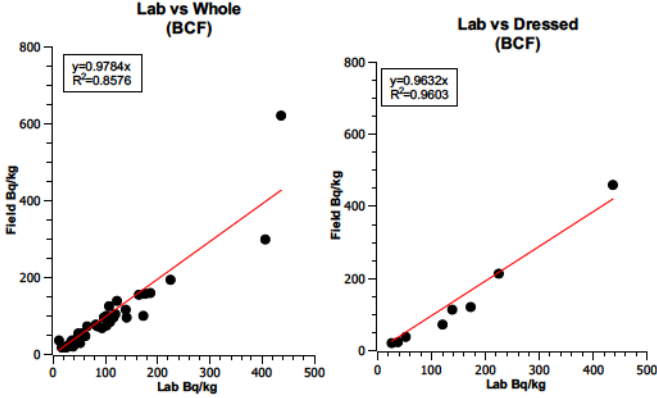


Figure 7: Lab vs field measured activity in Bq/kg. Field measurements assume Cs-137 is co-located with sodium and potassium.

Table 3: Uncertainty Contributions (in percent).

	QC Phantom		Deer	
	worst case	typical	worst case	typical
Counting	5	5	30	17
Stats				
Placement	2.4	2.4	2.4	2.4
Drift	12	0	12	0
Model Bias	-3	-3	-3	-3
Total Uncertainty	14	6	33	17

## 2.8. Measurement Uncertainty

The 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, detector drift, and the uncertainty in the counts-to-activity models. Each uncertainty is independent, therefore the total uncertainty is calculated in quadrature using:

$$\sigma_{total} = \sqrt{\sigma_{stats}^2 + \sigma_{placement}^2 + \sigma_{drift}^2 + \sigma_{model}^2} \quad (9)$$

An average QC calibration source has a measurement uncertainty of 7%, an animal with an activity of 1.6 pCi/g (59.2 Bq/kg) has a measurement uncertainty of 17%, and an animal in a worst-case scenario (low activity, high drift) has a measurement uncertainty of 33%, as shown in Table 3.

### 2.8.1. Counting Statistics

The percent uncertainty in the counting statistics ( $\sigma_{stats}$ ) is based on the Poisson distribution, as described in Knoll (2000), and calculated as:

$$\sigma_{stats} = \frac{\sqrt{LC_s + IC_s + RC_s + LB_{kg} + IB_{kg} + RB_{kg}}}{N_{Cs} - N_{Bkg}} \times 100 \quad (10)$$

where the  $IB_{kg}$  is the total number of counts in the ROI and the  $N_{Bkg}$  is the number of counts in the ROI less the sum of the counts in the regions to the left and right ( $LB_{kg}$  and  $RB_{kg}$ ) of the

ROI. The  $X_{Cs}$  and  $X_{Bkg}$  denotes animal and background measurements, respectively. This results in uncertainty between 6000% for samples near background, 30% near MDA (0.60 pCi/g (22.2 Bq/kg)), and 5% for samples with the activity of the calibration source (3.6 pCi/g (133.2 Bq/kg)).

### 2.8.2. Placement

The percent uncertainty of animal placement was determined by assaying a deer with measurable radioactivity twelve times. Between each measurement, the animal was removed and replaced on the detector system. This resulted in the total CPM uncertainty as:

$$\sigma_{total} = \frac{\sigma_{CPM}}{\mu_{CPM}} \times 100 = 0.034 \times 100 = 3.4\% \quad (11)$$

where  $\sigma_{CPM}$  is the standard deviation of the measurements and  $\mu_{CPM}$  is the mean CPM measurement. To calculate placement uncertainty, the following values were used in Equation (9):  $\sigma_{total} = 3.4\%$ ,  $\sigma_{stats} = 2.4\%$ ,  $\sigma_{drift} = 0\%$ , and  $\sigma_{model} = 0\%$ . The counting statistics uncertainty of 2.4% was calculated using the measured data and Equation (10). 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  $\sigma_{placement} = 2.4\%$ .

### 2.8.3. Drift

The uncertainty in the CPM is also impacted by any drift 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 4. This equation is of the form

$$\sigma_{drift} = 10.641 \times Eu^2 + 0.958 \times Eu \quad (12)$$

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 ( $\sigma_{drift}$ ) of 12%. If this Eu-155 value is exceeded, the system will prompt the user to recalibrate the system.

### 2.8.4. Model Bias

As described in Section 2.7.3, the average model bias is -3%.

## 2.9. Received DOE Dose from Consuming Animal Meat

Following DOE orders, the received DOE dose for consuming an animal is calculated from the portion of radioactivity attributed to DOE sources ( $A_{DOE}$ ).  $A_{DOE}$  is calculated by subtracting the background activity ( $A_{nonDOE}$ ) from the total activity ( $A_{Total} = conc_{meat}$ ).

$$A_{DOE} = A_{Total} - A_{nonDOE} \quad (13)$$

The background radioactivity is defined as the concentration in the animal's meat from Cs-137 that did not originate from US Department of Energy operations. This background radioactivity is mostly from above-ground nuclear tests performed in

Animal	<i>L</i>	<i>W</i>
Deer	0.4458	0.6304
Pig	0.5700	0.0000
Turkey	0.5113	-0.0132
Coyote	0.4700	0.0000

the 1950s and early 1960s by the US Department of Defense and foreign nations. For all animals, this non-DOE background is the decay-corrected value of 2.59 pCi/g (95.83 Bq/kg) calculated from January 1, 2013 to the current date (Gaines and Novak, 2016).

If the measured DOE radioactivity is greater than zero, the received DOE dose (in mrem) is calculated as:

$$Dose_{DOE} = A_{DOE} \times EdibleMeat \times G \times U \quad (14)$$

where the *EdibleMeat* is a linear function relating an animal's live weight (in lbs) to edible meat (in lbs) in the form:

$$EdibleMeat_{animal} = L \times LiveWeight_{animal} + W \quad (15)$$

where *L* and *W* are factors for each animal type, as shown in Table 4. Similar to dressed weight, these values were obtained using OKDOA (2008); PSU (2016); Brake et al. (1994); Ashley (2002).

For the dose calculation, it is assumed that the hunter consumes all of the edible meat. The *G* (Ingestion Dose) is a constant with a value of 5.03E-5 mrem/pCi calculated from the Effective Dose Coefficient for Ingested Water for Cs-137 (1.36E-8 Sv/Bq), DOE (2011b) p.A-20, and the Activity To Dose conversion (3.70E9 mrem/uCi), EPA (1988) p.121. The *U* (Unit Conversion) is 453.592 g/lbs.

The received DOE dose is stored in the database and associated with the hunter. For each subsequent animal the hunter receives, the dose value is included in their annual and lifetime doses and used to compare to the operator defined limits.

### 3. Results and Discussion

The development of this system to measure Cs-137 in wildlife at the Savannah River Site has resulted in a method that is sensitive to low radioactivity levels in wildlife and provides a good estimate of the uncertainty within the reported results.

After the initial development during one hunt season, the performance of this system has been good during subsequent hunt seasons. As part of the environmental reporting requirements at SRS, a portion of meat from every tenth animal (deer and pigs only) is sent to the laboratory for measurement. A comparison between the measurements made by this system and the laboratory is shown in Figure 8. It includes those animals where the measured activity was below the MDA (approximately 22.2 Bq/kg) of the field system.

The average uncertainty in the field-measurements is 20% of the reported value. The laboratory measurements, have an

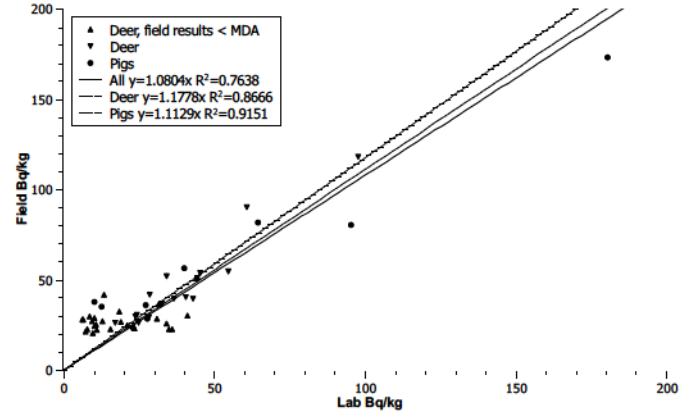


Figure 8: Lab vs field measured activity, in Bq/kg, for every tenth animal.

average uncertainty of 11%. This average field-measured uncertainty is higher than shown for a “typical” animal in Table 3 because during this hunt season, the average activity in these animals was lower, approximately 1.0 pCi/g (37.0 Bq/kg), versus 1.6 pCi/g (59.2 Bq/kg) for a “typical” animal. The field-measured values are on-average biased higher than the laboratory-reported values, 18% for deer and 11% for pigs. When the uncertainties are accounted for, the field results are satisfactory.

This system has similar goals as many other whole-body counting systems (Johnson and Ward, 1966; Woodburn and Lengemann, 1967; Zibold et al., 2001; Fesenko and Voigt, 2009; Chaiko, 2012; Wada et al., 2017) used to measure Cs-137 or other radionuclides in people and animals. To measure the amount of Cs-137 within animals many researchers bring the animals or portions of the animal to the laboratory (Zibold et al., 2001; Bondarkov et al., 2002; Beresford et al., 2008; ?; Wada et al., 2017; Gerke et al., 2020). These animals or samples are typically assayed over long time periods using high purity germanium detectors to get the most accurate measurement of the radionuclide of interest.

Our method is different from these in that we are estimating the dose that would be received from consuming the animal. In our case, an animal with enough radioactivity to cause a hunter to receive a dose has enough radioactivity for a one minute count-time to be sufficient to determine the concentration of Cs-137. In addition, the measurement time is constrained primarily due to the large number of animals measured (typically 20-40) after each hunt and the health concern of leaving a harvested animal uncooled while waiting to be measured (the average temperature on hunt days is 20 C). The short measurement time, and the fact that most of the animals measured have Cs-137 concentrations at or below MDA, cause a lack of counting statistics, which is the largest contributor to uncertainty in these measurements. To reduce this uncertainty, we could increase the assay time, however within the site-specific harvest outlined above, this is not feasible.

Our method is similar to other methods, such as Kapała et al. (2015); Wada et al. (2017), in that the detector is shielded to prevent background radiation from interfering with the mea-



surement. It is also similar to Kapala et al. (2015), among others, where a dose is being estimated based on meat consumption. Our system differs from Kapala et al. (2015) because we provide the results in a one-minute direct count of the animal for a specific individual versus a 25 hour count of a sample of the meat for a reference person. However, our method relies heavily on the accuracy of our MCNP model and assumptions about how the Cs-137 partitions within the animal.

The HDTS is an adaptation of a laboratory method to a field setting and is much improved over other methods for several reasons, primarily of which is the inclusion of an on-board check source. It is well known that NaI detectors drift, so ensuring an accurate number of counts of Cs137 is the critical step that drives both the reported Cs-137 concentration and dose and the uncertainty of the measurement. Ensuring the accuracy of the system is accomplished through the process of determining the ROI for the specific detector (in the lab) and how those counts may change as the detector drifts. Once the detector drifts, it is necessary to detect that drift and compensate for it. This is done by the on-board check source (Eu-155) and the daily QA. The daily QA sets the measured counts of the Eu-155, and ensures the Cs-137 peak is centered and all other systems are correctly functioning. The counts of Eu-155 are compared after each measurement and if they are significantly different the system warns the user and will not proceed until the underlying condition is corrected.

The other major improvement over other methods is the coupling of models with physical measurements. A model of how the detector responds to different sized animals containing a standard concentration of radioactivity enables the system to fit specific animals with differing weights and measured counts within the results of that model and use those results to report the concentration of radioactivity within that animal. The results are further enhanced by understanding the biochemical partitioning of the radionuclide of interest. Knowing where a particular isotope goes within the body, enables a better estimation of the concentration within that part of the body, without having to specifically measure that body part. These models provide a physical basis for justifying the results produced by the system.

Our system may be extended or improved through modifications to the method. For example, to measure the radioactivity in other animals or items, such as milk, a model of the geometry of that object and it's expected composition should be constructed within MCNP and the settings file updated with the model results. Another modification could be that if the age of the individual receiving the dose was known, the dose conversion factor used in Equation (14) could use the value listed for that age, as found in DOE (2011b), versus the currently used "Adult" value. Further changes to the software could be made so that only radioactivity concentration is reported or a different dose calculation to support the reporting requirements of other authorities could be made. Another possible change would be to use this system to monitor for different radionuclides, such as I-131. This would entail determining the region of interest and necessary count time to measure the radionuclide of interest.

## 4. Conclusion

The HDTS provides an all-in-one package for monitoring wildlife released to the public for Cs-137 at the Savannah River Site. It has a lower detection limit than the previous system for the same one minute count time and reports the uncertainty associated with each measurement. The model it uses to convert the measured activity to meat concentration is based on physics and biochemistry. This makes it possible to easily extend these measurements to other animals or objects just by modeling the geometry within MCNP and understanding where the radionuclide of interest is located within the object. In addition, this system can be adapted to the reporting requirements of other authorities by simple changes to the underlying software.

Further system specifications, operating instructions, and quality assurance documentation are found in Whiteside (2017, 2019a,b,c).

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