Analysis of Radioactivity in the Chernobyl Exclusion Zone Domestic Canine Population

An Interactive Qualifying Project Report

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by

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Abstract

A significant number of domesticated dogs were left to fend for themselves during the evacuations following the Chernobyl nuclear disaster. In the years following the disaster, enchroachment of wildlife has pushed the descendents of these dogs towards areas of human activity in and around the nuclear reactors outside of Pripyat. These dogs pose a threat to workers as bites from rabid dogs can prove deadly. Along with human danger and the impending closing of the sarcophagus around Reactor 4, the elimination of most human activity in the area creates the imperative for a solution to the dog problem of Chernobyl. Without intervention, they will breed with or be eaten by local predators creating environmental stress and altering the local biosphere. The mass elimination of these dogs is suboptimal due to the poor optics of such a campaign. The Clean Futures Fund has come to aid in the far more humane process of spaying and neutering the dogs and hopes to potentially be able to remove them from the effected areas. Our research utilized a limited number of fecal and hair samples in an attempt to estimate the radioactivity of these dogs and provide a decontamination scheme that would allow for their removal from the exclusion zone. While limited in certainty due to collection issues, low sample counts, and convenience bias, this paper is an effort to provide a first order estimation of a quarantine process such that the Ukrainian government would allow these dogs to be adopted into loving homes.

Contents

List of Tables

List of Figures

Acknowledgement of Contribution

These students left the project before its completion

Joseph LeBlanc

– 6 Hours in lab
– How did the Chernobyl Accident Happen?
– The Aftermath of the Incident
– Wildlife Effects

Yudith Sosa

– 6 Hours in lab
– The Dogs of Chernobyl

1. Background

1. Radiation and Radioactivity

1.1. Radioactivity

Radioactive decay is the process through which energetically unstable atoms release excess energy in a process called radiation. In order to reduce its total energy, an atom undergoing radioactive decay will eject mass from its nucleus in the form of alpha particles, protons, neutrons, or electrons. While radioactivity is a quantum stochastic effect and thus cannot be predicted for individual particles, it is useful to define decay constants for groups of radioactive atoms. Individual decays occur as independent events, thus the number of decays should be proportional to the amount of atoms of interest:

$$-\frac{dN}{dt} \propto N$$

From this relation it is possible to calculate a constant of proportionality:

$$-\frac{dN}{N} = \lambda dt$$

The solution to the above differential equation results in the common law of radioactive decay:

$$N(t) = N_0 e^{-\lambda t}$$

The decay constant is often not particularly intuitive with units of $\frac{1}{t}$ so it is useful to define two more related constants: $t_{1/2}$ and τ. $t_{1/2}$ is known as the half-life of a particular element. It is the time taken for a given amount of a particular nuclide to reduce its activity to half the initial activity and has units of time.

$$t_{1/2} = \frac{ln(2)}{\lambda}$$

τ is known as the mean-lifetime; the average time it takes for any single atom to decay, it also has units of time.

$$\tau = \frac{1}{\lambda}$$

As shown in Figure 2.4, we are able to pinpoint Cesium-137 as the main isotope of interest to our research. The half-life of Cesium-137 is approximately 30.08 years yielding a decay constant of $7.3 \cdot 10^{-10} s^{-1}$ and a mean lifetime for Cesium-137 atoms of 43.4 years.[1]

1.2. Gamma Radiation

While atoms may undergo many types of radioactive decay, our equipment is only sensitive to gamma radiation. Gamma radiation is a form of ionizing radiation that occurs as a byproduct of mass based nuclear processes such as beta decay. An atom undergoing radioactive decay often transmutes into a daughter atom in an excited state; the relaxation of this atom into its ground state causes the emission of a photon with energy equal the difference of state energies. A relevant example of this is the beta decay of Cesium-137 shown in Figure 1.1. In this case, the gamma photons that we should expect to detect are characteristic of the relaxation of Barium-137* created from the beta decay of Cesium-137. The expected energy of the gamma emission peak is 661.7keV represented by the photopeak in Figure 1.2.

Exposure to ionizing radiation is detrimental to health in both acute and chronic doses. Acute exposure can cause radiation sickness resulting in a host of serious complications and potentially death. Chronic exposure to radiation sources causes increased risks for

cancer, genetic defects, birth defects, and organ failure. Due to the damaging potential of ionizing radiation it is important to limit exposure to all involved parties.

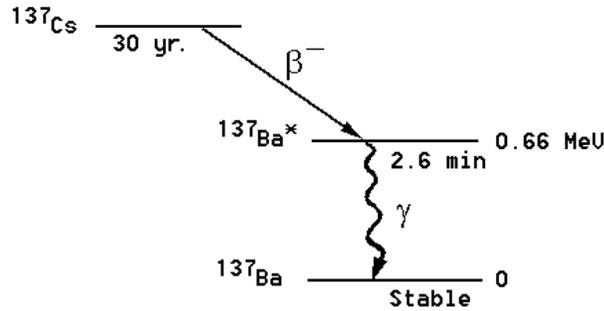Figure 1.1.: The Cesium-137 decay chain is a relevant example of a beta decay followed by gamma emission. This decay diagram shows the half-life, decay type, and associated energy of the gamma decay.[1]
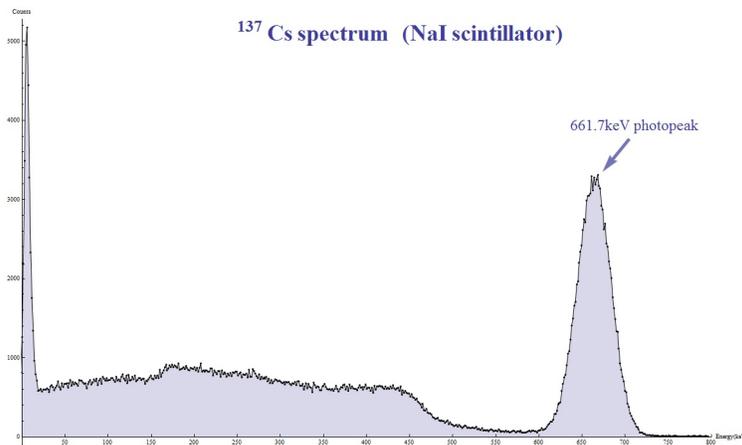

Figure 1.2.: The gamma spectrum of Cesium-137. While this spectrum is actually due to the relaxation of Barium-137*, it is colloquially known to be the Cesium-137 gamma spectrum as it is the parent of the initial β decay.[1]

2. The Chernobyl Disaster

2.1. How did the Chernobyl Accident Happen?

JOSEPH LEBLANC WITH TAYLOR TROTTIER

The accident that occurred at the Chernobyl nuclear power plant on April 26, 1986 is one of the worst industrial incidents of the 20th century with respect to environmental contamination. The Chernobyl Nuclear Power Plant is located near Pripyat, a town located presently in Ukraine.

A combination of cultural hubris and mechanical malfunction caused a meltdown of reactor No. 4, ultimately ending in calamity. The accident began during a late-night safety test simulating a blackout in the power station, during which all safety measures were intentionally deactivated. Reactor design flaws and an arranging of the core by operators in a way that was not suitable for the test overheated the fuel rods, which then led to the rapid transfer of disproportionate heat to the coolant water, creating a shock wave that ruptured the primary coolant system pipeline joins. Water in the cooling system quickly changed into steam, initializing a vaporization of part of the reactor fuel, creating a destructive explosion of steam and subsequent fires, which lasted for about nine days.[2]

2.2. The Aftermath of the accident

JOSEPH LEBLANC WITH TAYLOR TROTTIER

Most of the employees at the Chernobyl Plant lived in the town of Pripyat, located only 3 km from the site. Following the reactor meltdown, Pripyat's 50,000 people were evacuated, many of whom were families of the Chernobyl employees. In initial containment operations, two Chernobyl Plant engineers and five firefighters lost their lives.[2] According to the Journal of Public Economics, "...several hundred thousand people were exposed

to high radiation doses of 175 to 3000 times the average natural background radiation (350-6000 millisievert, mSv) in the vicinity of the reactor." Sievert, or Sv, is the SI unit of ionizing radiation dosage, measuring the health impact on a biological recipient. The level of dosage that towns surrounding Chernobyl received put their people at serious risk of cancer development and other health issues.[3] Following the initial accident, 134 containment workers expressed symptoms of acute radiation poisoning, and in the months that followed, 28 patients died from such complications, despite intensive therapy and 13 bone marrow transplantations. Compared to the bombing of Hiroshima in 1945, the nature of radiation contamination by the Chernobyl meltdown were very different. Figure 1.3 lists the wide spectrum of different isotopes that were released in Chernobyl.[2] Furthermore, there was irregular and patchy radioactive contamination of the environment. Even today, background radiation levels on the regional scale are highly variable, with some locations varying by two orders of magnitude at only hundreds of meters apart.[4] According to the Clinical Oncology journal, "The estimated release of radioactivity from the destroyed reactor reached a total of about 13 EBq (1 EBq = 1018 Bq)." That is 400 times more radioactive material than the Hiroshima bomb. A becquerel, or Bq, is the SI unit of radioactivity, which measures the quantity of nuclear decays per second. The largest constituent of the radiation contamination was caused by Cesium-137 activity, which amounted to around 64 TBq, or 1.7 MCi, of which Ukraine received 18%.[22]

2.3. Wildlife Effects

JOSEPH LEBLANC WITH TAYLOR TROTTIER

Today, there are many papers and journal articles that discuss the current state of wildlife populations in the Chernobyl zone. However, there is significant debate among scientists as to whether mammal abundances in the Chernobyl zone are in high levels or low levels. To elaborate, consider the Bulletin of the Atomic Sciences journal 67(2), written by Anders P. Møller PhD of the French National Centre from Scientific Research. MØreller ar-
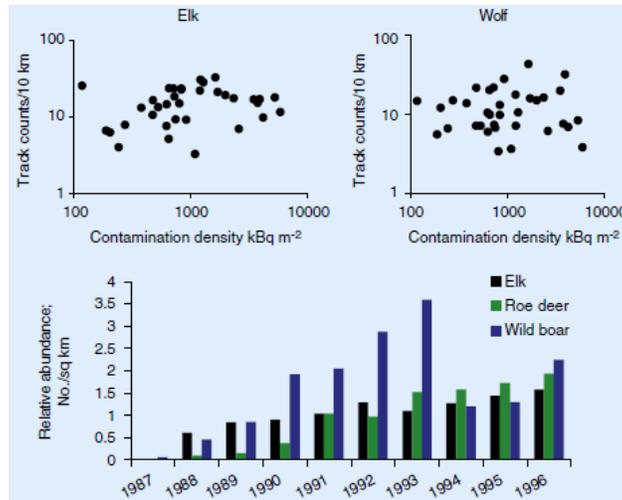
Figure 1.3.: This table shows the initial nuclide inventory released from the Chernobyl accident, updated as of April 26 1986.[2]

gues most organisms are capable of quickly overpopulating their habitats when a predator suddenly disappears from the ecosystem. In this case, the predators were the Chernobyl workers.[4] However, Møller argues that background radiation levels directly affect mammal abundance in the exclusion zone, correlating with a strong pattern of declining abundance and species richness.[4]

Some scientists argue that background radiation levels are not directly effecting local wildlife populations, and are instead thriving through the absence of humans. It could be possible for wildlife to develop a resistance to radiation through evolution, even among organisms that have only recently been affected by nuclear accidents because the intervening period of 30 years is sufficient for changes in phenotypes in standard selection experiments.[5] The Current Biology journal 25(19) argues that "extremely high dose rates during the first six months after the accident significantly affected animal health and reproduction at Chernobyl." This caused initial mammal abundance decline in the short term after the accident and you could expect this trend to continue as a consequence. But according to Current Biology's trend analysis of large mammal abundances, shown in Figure 1.4, there is no apparent long-term radiation damage to wildlife populations.[6]

Table 1
Principal radionuclides released due to the Chernobyl accident[a]

Radionuclide	Half-life	Activity released (PBq)
Noble gases		
^{85}Kr	10.72 years	33
^{133}Xe	5.25 days	~6500
Volatile elements		
^{129m}Te	33.6 days	240
^{132}Te	3.26 days	~1150
^{131}I	8.04 days	~1760
^{133}I	20.8 h	~2500
^{134}Cs	2.06 years	~47
^{136}Cs	13.1 days	36
^{137}Cs	30.0 years	~85
Elements with intermediate volatility		
^{89}Sr	50.5 days	~115
^{90}Sr	29.12 years	~10
^{103}Ru	39.3 days	>168
^{106}Ru	368 days	>73
^{140}Ba	12.7 days	240
Refractory elements (including fuel particles)		
^{95}Zr	64.0 days	84
^{99}Mo	2.75 days	>72
^{141}Ce	32.5 days	84
^{144}Ce	284 days	~50
^{239}Np	2.35 days	400
^{238}Pu	87.74 years	0.015
^{239}Pu	24 065 years	0.013
^{240}Pu	6537 years	0.018
^{241}Pu	14.4 years	~2.6
^{242}Pu	376 000 years	0.00004
^{242}Cm	18.1 years	~0.4

Data are inferred from [2,8,16,19].
[a] Decay corrected to 26 April 1986.

Figure 1.4.: Animal population trends for the areas around Chernobyl for years following the accident[6]

3. The Dogs of Chernobyl

YUDITH CHUM-SOSA WITH TAYLOR TROTTIER

There are many stray dogs in Chernobyl that were left behind by their owners. According to Zinaida Kovalenko, a re-settler from Chernobyl, after the incident everyone evacuated, "but they left their dogs and cats".[7] The owners did not leave them because they wanted to but because they had to; since, they were told that they could only bring whatever they can carry, and that excluded pets. Therefore, as a result there were many pets left to wander the streets and the soviet soldiers were ordered to shoot and kill the abandoned dogs.

The soldiers went ahead and shot the dogs but they were not successful in killing all of them. The dogs that survived the culling had to now defend for themselves against the wolves that lived around the area; being driven out of the woods they went to seek refuge in the Chernobyl Exclusion Zone. The dogs made the Exclusion Zone their home and now the descendants of these dogs can today be found around the nuclear plant.[8] Forced to fend for themselves they became susceptible to an array of health problems. Many are malnourished, and have rabies due to the rabid wild animals in the zone that spread it to them.[9] Overall, they have a short life expectancy, with many not living beyond the age of six.[10]

In time, the workers at the power plant became fond of these dogs and started to take care of them by giving them food and sometimes providing them shelter when it gets too cold outside. And since, many of the dogs have not had their rabies vaccine, they could become a hazard to the workers at the power plant, because by just interacting with them the workers run a risk of contracting rabies from them.

Another problem concerning these dogs is that many are not spayed or neutered causing the population of these strays to get out of control. In result, there are over 30,000 stray cats and dogs that live around the reactor. Thus one of the ways that the nuclear plant is protecting their workers and controlling the ever growing number of strays is by hiring someone to capture and cull the dogs. The culling of the dogs is a rather extreme way to control the population, which is why it is important to bring more light into this issue in order for that there can be funds that can help spay or neuter the dogs.

This is why Clean Future Funds has made it their mission to raise funds for that they can bring over veterinarians that can give out rabies shots to the dogs, as well as spay and neuter them in order to control the population.[8] The funds will be used to not only bring in veterinarians but to also help purchase the vaccines, and anesthesia needed in order to perform the surgeries. This will hopefully help stop the culling of the strays, and bring down the current population of strays to a smaller and much more manageable size.[10]

The ultimate goal is to be able to put these strays up for adoption, but however there are few hurdles in the way. The major problem is that the Ukrainian government does not allow animals to be removed from the Exclusion Zone, therefore special permission has to be granted.[9] A step to be able to do this is to investigate these dogs a little more through fecal and hair samples to determine if they are safe to be relocated to other countries, in order to be able to go through the adoption process.

2. Methods

1. Collection of Samples

Sample Collection was performed on site in Pripyat Ukraine by workers of the Clean Futures Fund. Initially, fecal samples were intended to be collected from dogs to be spayed, but this proved impossible within the scope of the project. Opiate based sedatives were used to incapacitate dogs for collection and spaying. The opiates caused constipation preventing the dogs from passing fecal matter in a reasonable timeframe before being returned to the reactor site. Because of this, uncorrelated fecal samples were collected from the areas around the animal hospital. Samples were collected and labeled with collection date, cardinal orientation to the hospital, and a number from 1-9 (note that sample 8 seems to have been lost somewhere in the collection process. Hair samples were collected from dogs that were spayed and neutered by the veterans of the CFF. Upon receipt hair samples were labeled in two series, Y-XXX and O-XX (Note: we have have no context for this labeling scheme). Some of samples in the series seemed to be lost in the process of collection and transport to the United States. Of the approximately one hundred samples received, thirty seven were tested in the time given. A table of scanned samples can be found in Appendix Table A.3

2. Preparation of Samples

All samples were prepared identically and under similar conditions. All samples were tested in disposable 56mm diameter petri dish tops. Images are included of a typical setup

below. A mass was taken before adding samples to the petri dish. Hair Samples were transfered from paper bags to the petri dish in an even distribution and the bottom of the petri dish placed on top with a circular lead weight to compress the hair into a denser profile. Fecal samples were placed in a similar setup, but were first crushed in whirlpak bags with lead bricks to a fine powder. While it wasn't necessary for the fecal samples the lead weight was placed on them for consistency in measurement. Petri dishes were massed again to determine the sample mass before loading it into the detector. The petri dishes were placed in the center of the detector and the lead shield closed.

Figure 2.1.: Empty petri dish

Figure 2.2.: Simulated loaded petri dish with lead weight placed in detector

3. Radiation Detection and Measurement

Effective collection and measurement of gamma radiation is an essential factor in the reliability of data. Two detectors were used to scan samples for this project, a Canberra LynxNaI analog sodium iodide based detector, and a Canberra Osprey digital sodium iodide detectors. Detector type and geometry determine a system's overall collection efficiency and will later be used to guide analysis.

3.1. NaI(Tl) Scintillator Detector Mode of Operation

The Canberra Lynx NaI, and Osprey are both Thallium-doped Sodium-Iodide scintillation detectors. NaI(Tl) is the most widely used scintillation material due to it being relatively cheap and easy to produce. When exposed to ionizing radiation, the NaI(Tl) crystal emits photons that are guided to a photomultiplier tube amplifying the optical signal. These detectors operate on the principle of scintillation. A scintillating material excited by ionizing radiation emits light. Scintillation is a side effect of the electron band structure found in most crystals. Most pure crystals have a distinct band structure, shown on the left of Figure Figure 2.3, in which there a "band gap" between the valence and conduction electron bands. The valence band contains electrons bound to their atoms whereas the conduction band only contains atoms that have been excited enough to be liberated from their atoms and allowed to travel freely. Electrons in a crystal doped with an activator, have a band gap littered with interstitial energy states in the so called "forbidden zone".
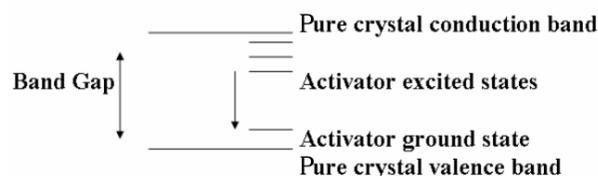

Figure 2.3.: The left half of the above image illustrates the valid electronic energy states in a pure crystalline structure while the right half of the image shows energy states created in the band gap by adding impurities to the chemical composition of the crystal.

When an electron is excited into a higher energy band a positively charged hole is left behind. This pair is called an exciton; the exciton quasi-particle moves through the crystal lattice until encountering the dopant atom which quickly absorbs the energy of the exciton emitting a characteristic scintillation light. The wavelength of the light emitted is determined by the impurities of the crystal. The amount of light emitted from the crystal is determined by the energy of the incoming photon as it scatters inside the crystal. The higher energy the photon, the more electrons it is able to scatter inside the crystal allowing a greater production of secondary photons. The photomultiplier tube amplifies the secondary photons and outputs a voltage based on the number of photons created. The analog (in the case of the Lynx) or digital (in the case of Osprey) MultiChannel Analyzer (MCA) then interprets this signal as counts of specific energies. In Pulse Height Analysis (PHA) mode, the detector determines the energy of the detected photon by by the amplitude of the photomultiplier pulse. This data is then sent over ethernet cable to the computer that interprets and saves this data.[1]

3.2. Detector Calibration

Calibration of detectors is important to allow the collection of accurate and reproducible data. Detector calibration for sodium iodide detectors involves the use of known check sources to modify the gain on amplifiers that receive a signal from the detection apparatus. Multi Channel Analyzer (MCA) gamma spectrometers in Pulse Height Analysis (PHA) mode monitor channels based on amplitude. Using a source of Cesium-137 with known activity located at the center of the detector, the gain is calibrated to locate the centroid of the detected spectrum at $661.7\mathrm{keV}$. The centroid, which is the center of "mass" of the peak, must be selected due to uncertainty in the energies of collected gamma photons. While one would expect that the transition energy of resultant Barium-137 to be constant, thermal fluctuations in the detector crystals will cause shifts in energy levels and vibrational modes in the crystal causing uncertainty in the measurement. Luckily, the thermal disturbances will be normally distributed and the peak can be modeled as a scaled Gaus-

sian. Cesium-137 was selected as the calibration source due to it currently being the main activity source in Chernobyl, and the only remaining long lived gamma emitter found in significant quantities.[11]
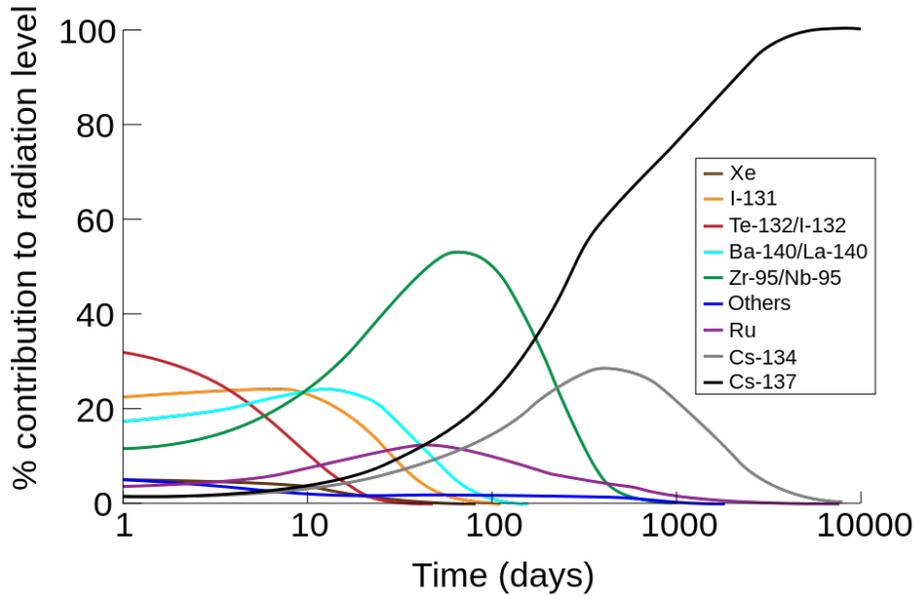

Figure 2.4.: Time vs Air Dose at Chernobyl site

3.3. Specific Hardware

Both of our detectors use a Bicron 3x3 NaI crystal for detection. The Lynx NaI then uses an Ortec 296 Scintipac photomultiplier tube with preamplified analog outputs to the Lynx NaI Box. The Osprey has its own integrapted photomultiplier and has digital output. Both the Lynx NaI and the Osprey provide digital data to the computer over an ethernet connection. Both detectors were contained inside shielded lead housings in order to reduce background radiation and lower the noise floor.

Figure 2.5.: Canberra Osprey Detector

Figure 2.6.: Lynx NaI Detector

Figure 2.7.: Ortec 296 Scinitipac photomultiplier and analog preamplifier

Figure 2.8.: 3x3 Sodium Iodide crystalr

Figure 2.9.: Our Canberra Osprey

Figure 2.10.: Lead Shielding named Teddy

3. Analysis

1. A Note on Statistical Analysis

Our analysis of all data, especially that of the fecal samples, is plagued by a number of factors that eliminate all certainty from any statistical analysis performed. The low number of samples, high variability, and convenience sampling alone make prediction quite difficult. We have performed analysis as if our data set was larger and randomly sampled.

2. Background Removal

In order to allow the collection of only relevant spectra, we took background images for each detector. These scans were used as a baseline for detector noise and natural background radiation. All scans were first divided by their scan time to allow a unit comparison of Counts per Second or CPS. The background scan was then averaged for the seven values above and below it to allow for a smooth background to be taken. This was done to avoid large differences between channels caused by detector based effects and thermal fluctuations that do not reflect the physically expected smooth distribution. This is acceptable because we expect quantized energy effects on a scale so small that our detector resolution is far too low to detect. In this case we expected a smooth detection distribution including peaks which have a Gaussian shape.

3. Peak Detection

Peak detection is critical to the effective characterization of nuclear materials and their activity. In the context of this project the only expected peak will be that of cesium-137. Because of this, the peak detection algorithm finds the maximum value of all the data and records this location. Due to the fact that the distribution of a decay peak is normally distributed a relation can be drawn between the standard deviation and full width at half max Equation 3.1. The full width at half max in this data represents the energy range where counts exceed half the maximum value. Using the relationship Equation 3.1, we can calculate the 95% peak interval and calculate the sum of counts over this region to get a reasonable estimate of the net activity of the sample. This is discussed further in the MATLAB code appendix section 2.

Also of importance to note is that the peaks were not detected directly at $662\mathrm{keV}$. While in a perfect world it would have been possible to detect peaks directly at the expected points our testing was plagued with temperature fluctuations due to volatile outdoor temperatures and the poor climate control of our test location. Due to these fluctuations larger than expected drift on the scale of many hours caused uncontrollable shifts of detection energies. Optimally the shift experienced would be below 1%, we had shifts of about 1.5%.

$$[h]\sigma = \frac{FWHM}{\sqrt{2 \cdot \ln 2}} \tag{3.1}$$

After the extraction of the peak, the count rate was multiplied by 2 in order to account for the thin disk approximation, and divided by 0.2 to account for the efficiency of NaI detectors. The thin disk approximation is based on an isotropic spherical distribution of radiation. From a disk with radius much greater than its height, approximately all the radiation will be emitted from above and below the faces of the disk. In this case it is acceptable to double the count rate in order to account for radiation emitted away from the detector. The efficiency of our sodium iodide detector is just over 20% across the entirety

of the face being exposed to the sample, thus it counts can be slightly overestimated by dividing countrate by 0.2.

4. Activity Found From Hair

No measurable activity was found in any hair tested. Confidence in this measurement is quite high as nearly forty samples were tested and returned no measurable radioactivity. The hair samples were taken from dogs being spayed and neutered. Because they were being prepped for a surgical procedure, it is to be expected that any radioactive dirt was lost in the washing process. Due to the fact that it distributes throughout the soft tissues of the body, cesium was not expected in clean hair samples. A summary of all hair scans can be found in the appendices Table A.3 , Table A.4. The gamma spectra of all hair scans are located in the appendices section B.

5. Activity Detected From Feces

Unlike our hair samples, we expected to see a measurable amount of cesium excretion in fecal samples. Every fecal sample measured showed some level of activity though a significant portion were found to have activity less than or equal to $1\,\mathrm{Bq\,g^{-1}}$. Two outliers, sample 4 and 5, have activities 3 and 6 times greater than this. Summarized in Table 3.1.

Table 3.1.: Fecal Scan Peak Data, note that CPS/g is a specific activity and gives a valid comparison basis for the data and all counts are scaled for geometry

Sample	Mass(g)	Peak	FWHM (keV)	STD (keV)	2StdSum (CPS)	Sum/g(CPS/g)
1	2.6	654.39	630.371	267.6939	0.53809	0.152
2	3.85	658.39	46.03	19.5471	1.6929	0.45
3	5.65	658.39	46.03	19.5471	6.168	1.12
4	10.22	655.39	45.02	19.1182	30.439	3.03
5	9.97	654.39	45.02	19.1182	55.9769	5.71
6	5.01	653.39	624.371	265.146	0.71218	0.16
7	3.02	654.39	623.371	264.7213	0.29333	0.08
9	5.12	652.39	44.02	18.6936	3.1212	0.63

6. Decontamination and Quarantine

6.1. Acceptable Levels of Exposure

As a radionuclide, Cesium-137 is inherently carcinogenic and has exposure limits set by the United States Nuclear Regulatory Commission. According to Appendix B of the NRC Regulations Title 10 Code of Federal Regulations, the maximum yearly occupational exposure to Cs-137 orally is 100μCi. Oral exposure is the most likely route of exposure, as ingestion through crosscontamination is far more likely than exposure to any measurable airborne dose originating from the dogs. Exposure to 100μCi of cesium causes an equivalent full body dose of 50 mSv. This is approximately fifty times the allowable annual dose to the public of approximately 1 mSv. This dose is approximately equal to 500 chest x-rays.[121314] To avoid the need for licensure and import import restrictions, dogs must not be radioactive enough to expose anyone to even 1 mSv of radiation. In order soundly satisfy this standard, the total activity of any single dog must be less than 40μCi.[1514] Based on this estimate an **adoptable dog needs to have a total mass of Cesium-137 less than 0.5μg**.

6.2. Cesium Lifetime in Dogs

We can estimate the lifetime of radioactive cesium in exposed dogs using data from a series of studies performed by the United States Department of Energy during the 1950s-60s. We will then use these estimations to provide a sample quarantine procedure for dogs with activities similar to the ranges we found. Based on the report, cesium was found to behave in a two tailed manner upon exposure. Approximately 20% of cesium was excreted within one day, with the remaining 80% being absorbed and distributing itself throughout the body. This 80% was found to have an upper bound on half-life of 47 days, this time increased with the age of the dog. The excretion of cesium was found to be split urine and feces at a 10:1 ratio respectively.[16]

6.3. Time to Negligible Cesium Exposure

The expectation that cesium behaves in the body similarly to potassium must be heavily relied upon along with the expectation that it distributes itself similarly in tissues. This is due to a drought of data for cesium and a relative glut of data for potassium behavior in the body.

With an excretion rate of 10:1 between urine and feces, activity found in the the feces must be scaled by a factor of 11. From here we are able to estimate, using potassium concentrations found in the urine, the unit activity of cesium in bodily tissues. Children with a healthy concentration of potassium have a urine excretion concentration of approximately 1400 mg $L^{-1}day^{-1}$. The concentration of most bodily tissues is roughly 6000 mg L^{-1}. Assuming an approximate density for both dog and its urine to be 1kg L^{-1} (a fair assumption for mammals) the ratio of potassium in the body to the urine can be found to be 4.3:1 g kg^{-1} or 4.3:1 mg g^{-1}. It is quite a stretch to assume that concentration ratios of cesium and potassium would be the same, but we lack a better way to estimate internal concentration. Combining these ratios we arrive a the total concentration of cesium in any given dog to be approximately 44 times that of the concentration in their given fecal sample. Using this estimation and the specific activity of pure Cesium-137 to be 3.12TBq we have calculated the approximate mass of cesium in a dog of a range of given weights summarized in Table 3.2

Sample	Spec.Act.	Body Activty	Rel.Act. Cs-137	Cs-137 µg (10kg)	Cs-137 µg (20kg)
Sample 1	0.15	6.67	2.08e-12	0.02	0.04
Sample 2	0.45	19.95	6.23e-12	0.06	0.12
Sample 3	1.11	49.14	1.53e-11	0.15	0.31
Sample 4	3.02	133.14	4.15e-11	0.42	0.83
Sample 5	5.70	251.28	7.85e-11	0.79	1.57
Sample 6	0.14	6.577	2.05e-12	0.02	0.04
Sample 7	0.07	3.317	1.03e-12	0.01	0.02
Sample 9	0.62	27.52	8.60e-12	0.09	0.17

Table 3.2.: The above table shows the amounts of cesium that could be estimated for dogs of different weights. All masses are in micrograms and activities in Becquerel

Based on our limited information and zeroth order estimation, we can now provide a range of reasonable times for quarantine. Using the threshold 0.5 μg, the worst case dog would need to be quarantined for a maximum of 3 half-lives. Assuming the longest experimentally measured biological half-life this time is just over four months, or approximately 130 days. In order to reach levels ten times below the upper threshold of activity, we must quarantine the dogs for five half-lives or 215 days. Given that most dogs, even those that live in and around the reactor, live at least 6 years, a quarantine of even 215 days is an amount of time such that an adoptive family could love this animal for an appreciable amount of time. The quarantine process will be approximately the same to that of a normal shelter, feed and water dogs in a safe and comfortable location. Special precautions will need to be taken to remove urine and feces from the premises. While the amount of radioactive material these dogs will excrete is low, it is important to prevent further spread of potentially harmful nuclides. The collection of urine will prove most difficult as containment of the excreted liquid and preventing its comingling with noncontaminated water supplies requires collection and filtration infrastructure.

4. Conclusion

Based on limited information, we have determined that potentially all the dogs living in the Chernobyl exclusion zone could be transplanted after a quarantine of less than one year. With the low concentration of Cesium-137 in the tested dogs and a relatively short biological half-life in dogs, the worst option may yet be avoided. If allowed by the Ukrainian government, these dogs are nearly guaranteed to be adopted by some of the many Chernobyl buffs around the globe. While the Clean Futures Fund is more concerned with these dogs not reproducing, it would be extremely fulfilling to move spayed and vaccinated dogs into homes across the globe. At least then something positive will have come from this failure of man.

Appendices

A. Scan Data

1. Fecal Scan Mass

Taylor Trottier with Joseph LeBlanc and Yudith Chum-Sosa

Table A.1.: Fecal Scan Masses

Sample	Petri Mass	Total Mass	Sample Mass
Sample 1	8.7	11.3	2.6
Sample 2	8.81	12.66	3.85
Sample 3	8.63	14.28	5.65
Sample 4	8.46	18.68	10.22
Sample 5	7.6	17.57	9.97
Sample 6	7.74	12.75	5.01
Sample 7	7.59	10.61	3.02
Sample 9	7.56	12.68	5.12

2. Fecal Scan Peak Data

Table A.2.: Fecal Scan Peak Data, note that CPS/g is a specific activity and gives a valid comparison basis for the data

Sample	Mass(g)	Peak	FWHM (keV)	STD (keV)	2StdSum (CPS)	Sum/g(CPS/g)
1	2.6	654.39	630.371	267.6939	0.53809	0.152
2	3.85	658.39	46.03	19.5471	1.6929	0.45
3	5.65	658.39	46.03	19.5471	6.168	1.12
4	10.22	655.39	45.02	19.1182	30.439	3.03
5	9.97	654.39	45.02	19.1182	55.9769	5.71
6	5.01	653.39	624.371	265.146	0.71218	0.16
7	3.02	654.39	623.371	264.7213	0.29333	0.08
9	5.12	652.39	44.02	18.6936	3.1212	0.63

3. Hair Scan Log

Table A.3.: Hair Scan Data: Y Series and Background

Sample	Pre Cal	Post Cal	Drift %	Empty Mass	Full Mass	Mass
Y001	662	660.54	0.22	7.54	9.08	1.54
Y002	662.18	663.72	0.23	7.74	8.46	0.72
Y003	661.99	664.24	0.34	7.63	8.61	0.98
Y004	662.07	663.4	0.20	7.84	8.85	1.01
Y005	661.9	662.12	0.03	7.54	9.04	1.5
Y006	662	660.5	0.23	7.51	8.67	1.16
Y007	661.82	660.28	0.23	7.54	8.89	1.35
Y008	662.09	664.68	0.39	7.79	9.12	1.33
Y009	662	664.97	0.45	7.63	9.34	1.71
Y010	661.72	664.21	0.38	7.57	8.36	0.79
Y011	661.96	664.68	0.41	7.57	8.76	1.19
Y012	661.98	657.28	0.71	7.9	9.07	1.17
Y013	662.01	658.21	0.57	7.89	9.32	1.43
Y014	662.09	659.96	0.32	7.82	9.12	1.3
Y015	662	661.72	0.04	7.58	8.99	1.41
Y016	662.03	664.23	0.33	7.58	8.84	1.29
Y017	661.8	662.49	0.10	7.55	8.75	1.2
Y018	661.9	665.6	0.56	7.6	8.68	1.08
Y019	662.03	662.27	0.04	7.7	8.81	1.11
Y020	661.92	658.7	0.49	7.6	8.78	1.18
Y021	662	660.29	0.26	7.61	8.51	0.9
Y022	661.98	658.21	0.57	7.55	8.75	1.2
Y023	662.04	663.65	0.24	7.7	9.02	1.32
Back-T-24	662.07	666.52	0.67	0	0	0
Back-23-24	662	659	0.45	0	0	0
Back-T-48	662.08	656	0.92	0	0	0
Back-23-48	661.9	660.5	0.21	0	0	0

Table A.4.: Hair Scan Data: O Series

O-35	661.93	662.96	0.16	7.59	7.84	0.25
O-36	661.96	662.8	0.13	7.74	7.89	0.15
O-37	661.92	660.42	0.23	7.55	8.45	0.9
O-38	661.82	662.4	0.09	7.79	7.91	0.12
O-39	662.05	660.63	0.21	7.57	7.92	0.35
O-40	661.97	659	0.45	5.81	5.86	0.05
O-42	661.95	659.04	0.44	5.9	6.05	0.15
O-44	662.15	657	0.78	5.89	6.03	0.14
O-45	661.98	662.1	0.02	5.96	7.03	1.07
O-46	662.12	667	0.74	5.86	6.51	0.65
O-47	662.06	665.2	0.47	5.86	6.14	0.28
O-48	661.9	667	0.77	6	7.02	1.02
O-49	662.1	666	0.59	5.81	6.16	0.35
O-50	661.9	659	0.44	5.89	7.49	1.6

B. Raw Graphs

1. Background Data
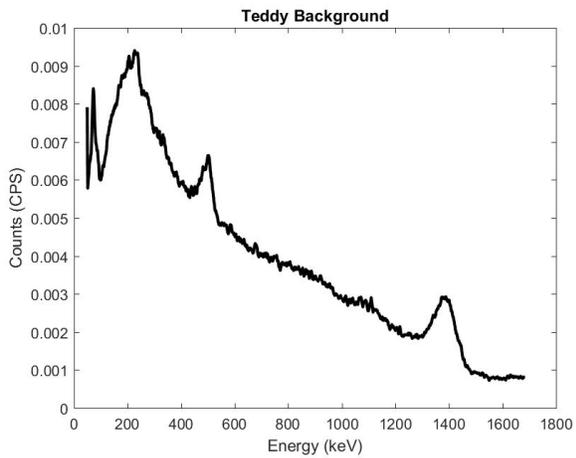
Figure B.1.: Background Teddy 24 Hrs
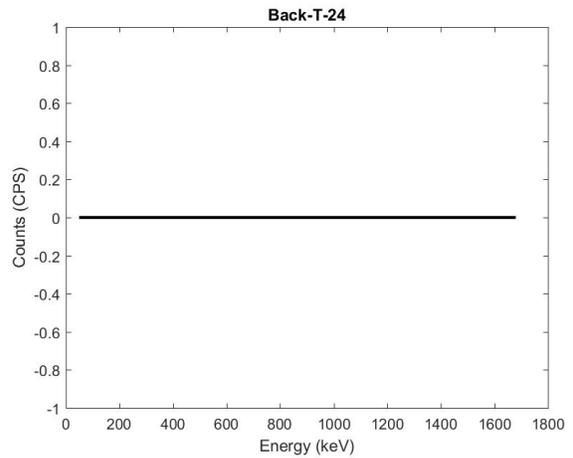
Figure B.2.: Background - background removed
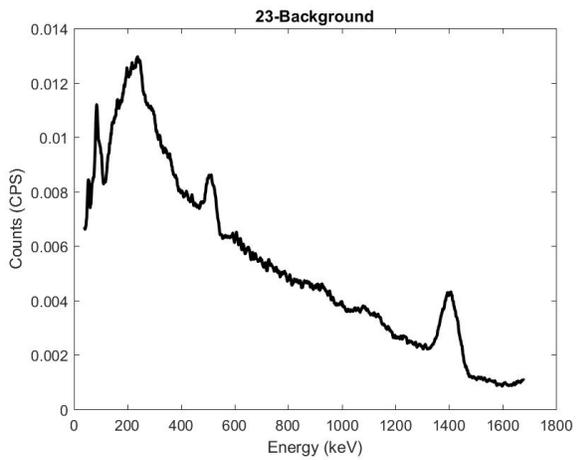
Figure B.3.: 23 Background after removal
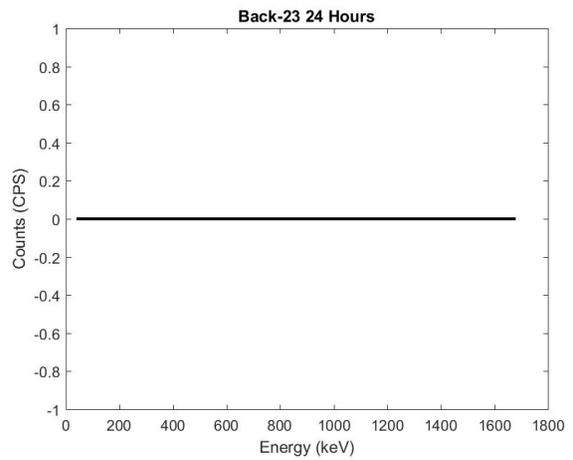
Figure B.4.: Teddy Background after removal

2. Fecal Graphs: Background Removed
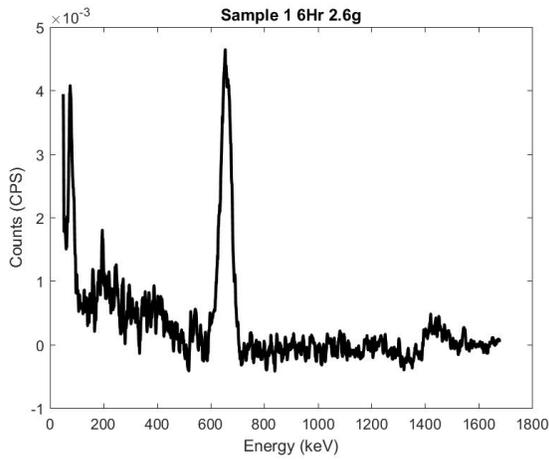
Figure B.5.: Fecal Sample 1, From Teddy
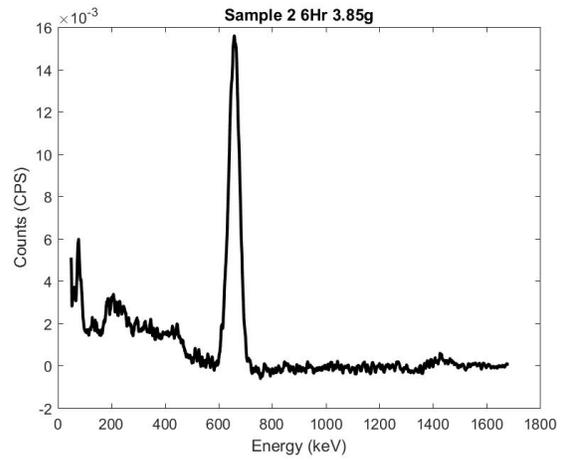
Figure B.6.: Fecal Sample 2, From Teddy
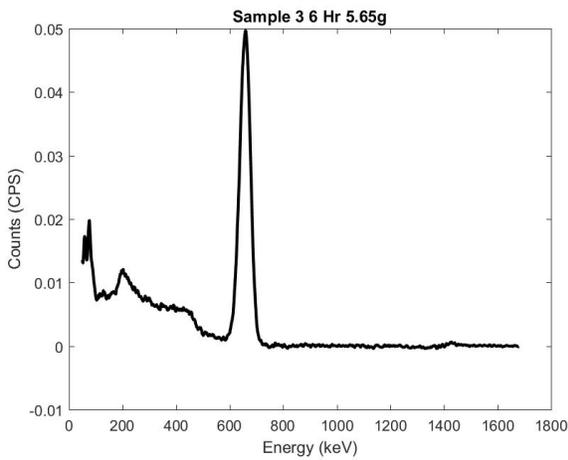
Figure B.7.: Fecal Sample 3, From Teddy
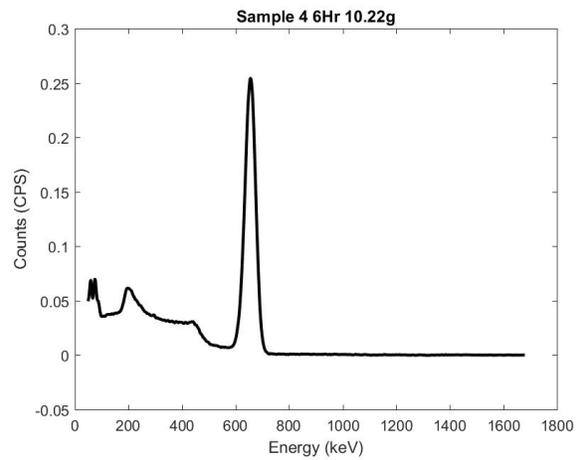
Figure B.8.: Fecal Sample 4, From Teddy
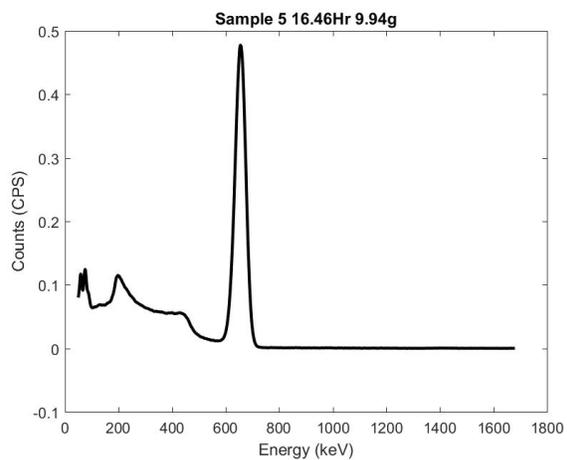
Figure B.9.: Fecal Sample 5, From Teddy
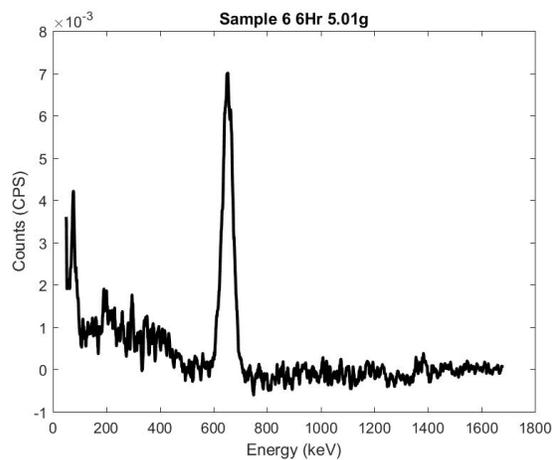
Figure B.10.: Fecal Sample 6, From Teddy
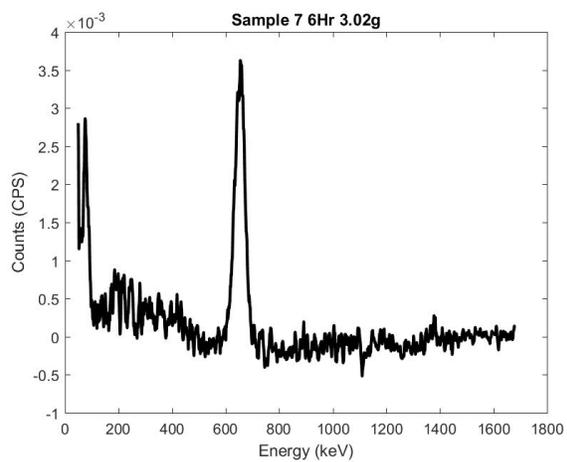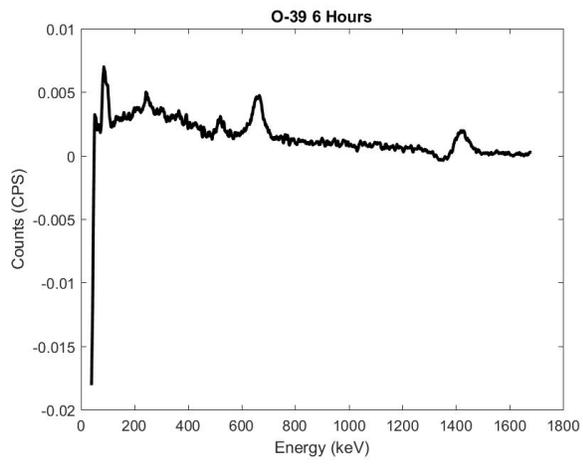

Figure B.11.: Fecal Sample 7, From Teddy
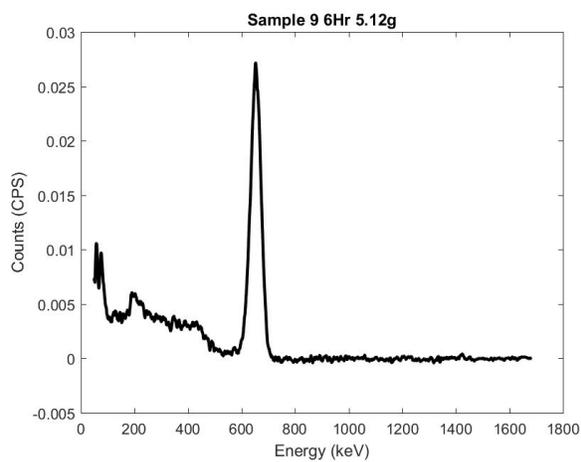
Figure B.12.: Fecal Sample 9, From Teddy
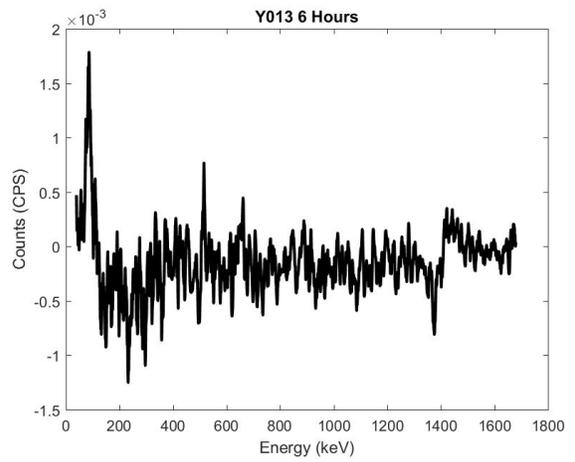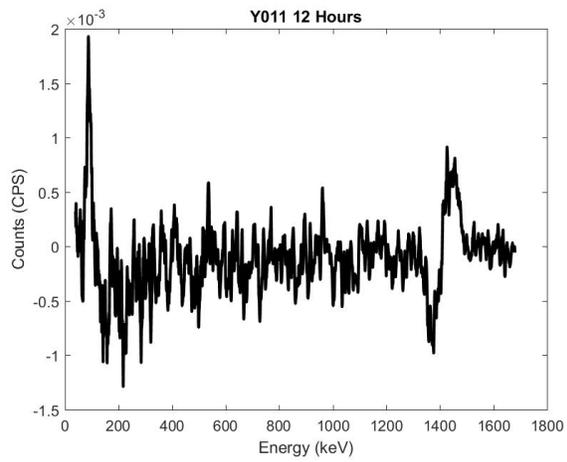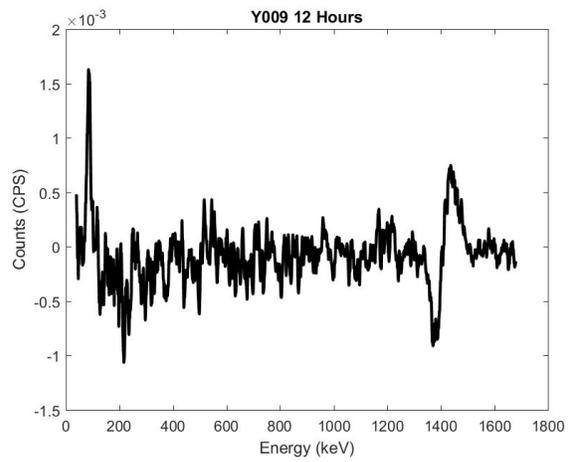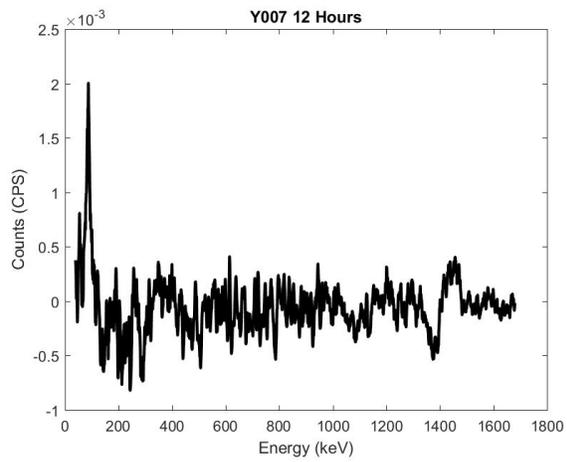
3. Hair Graphs (Teddy) : Background Removed
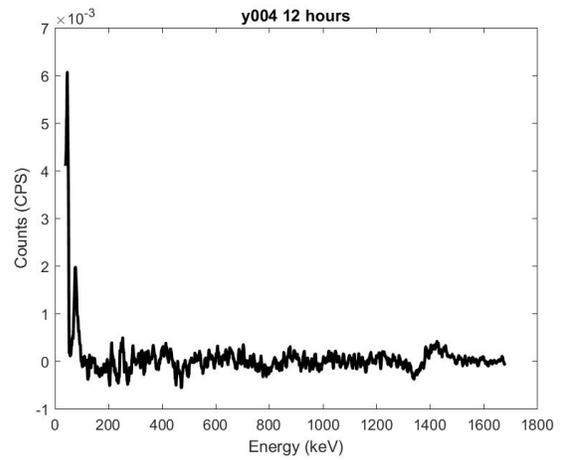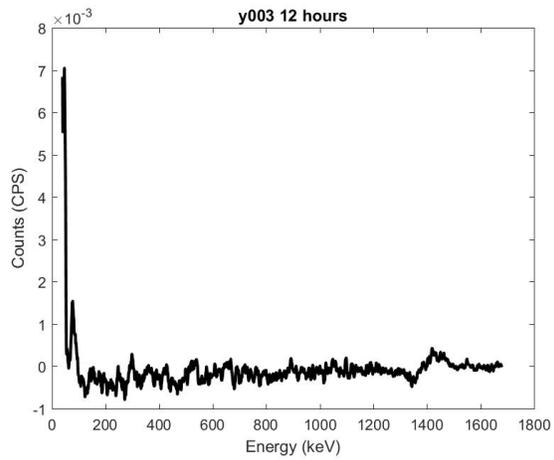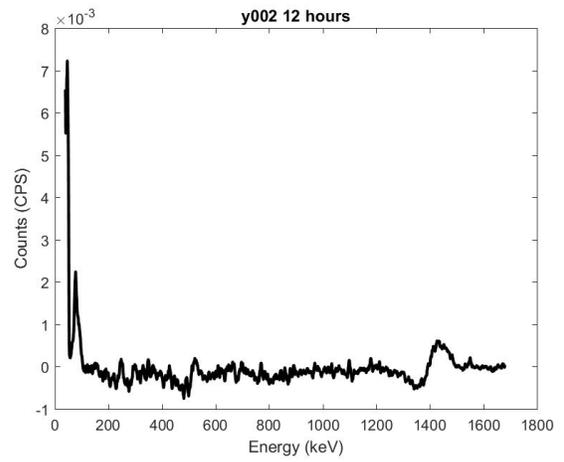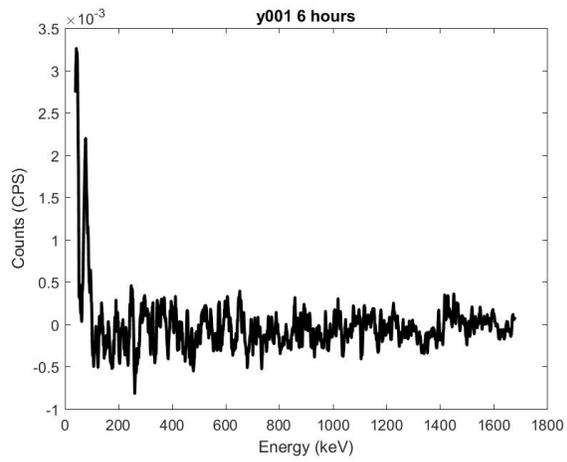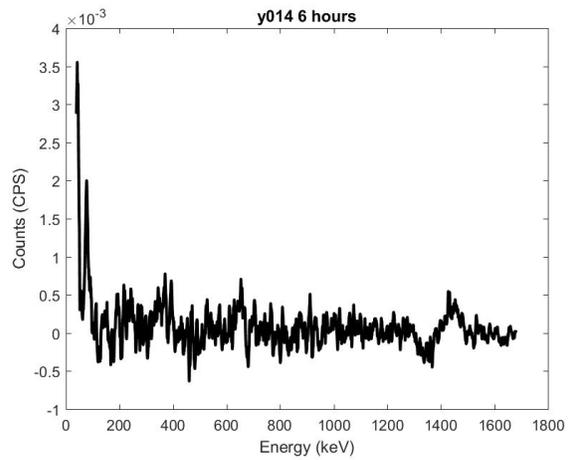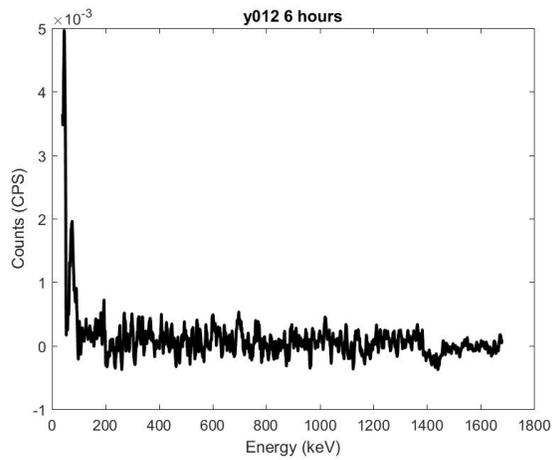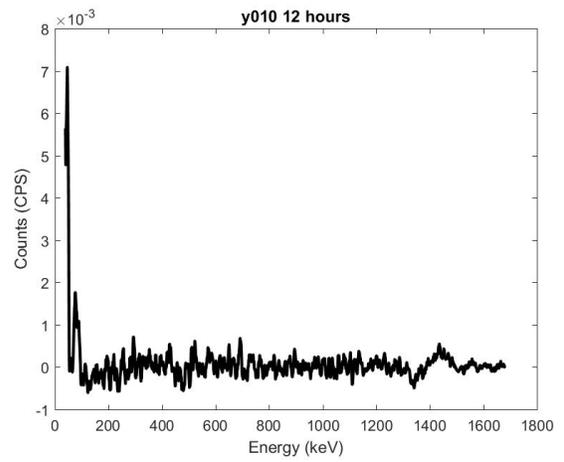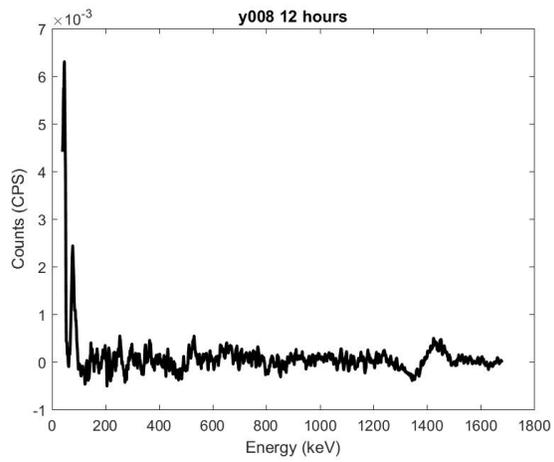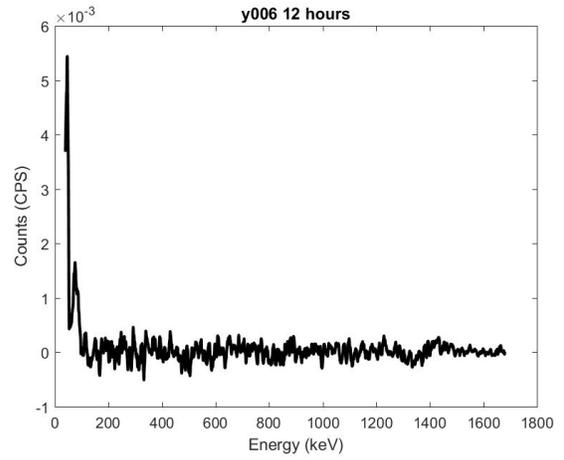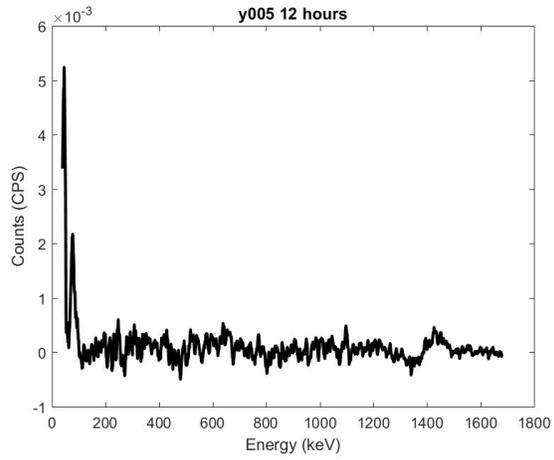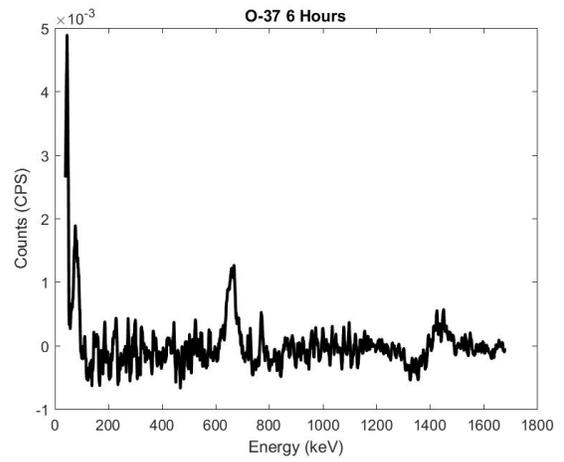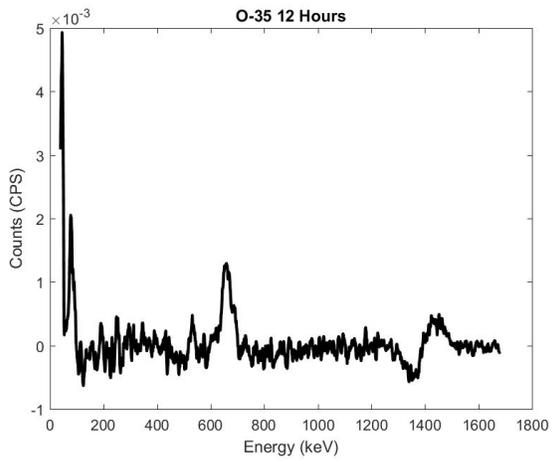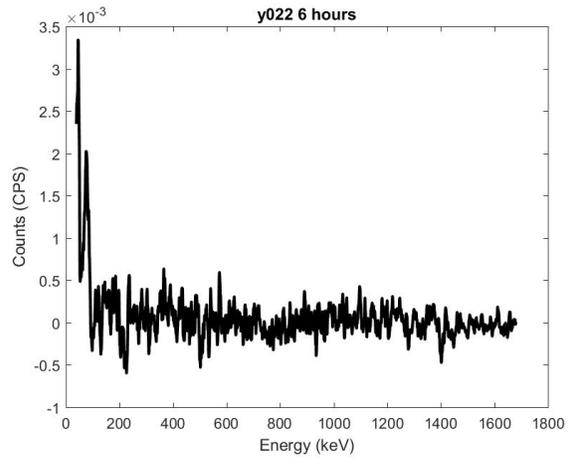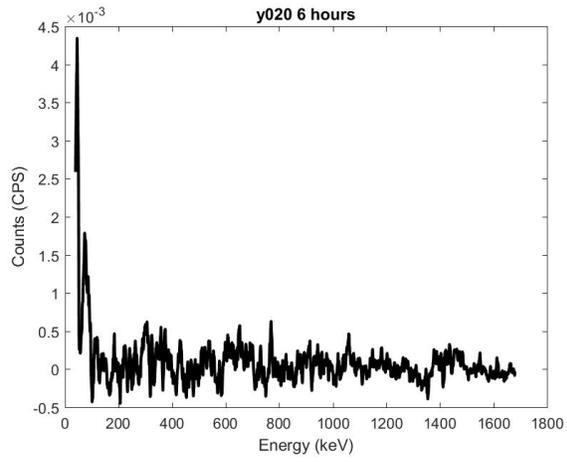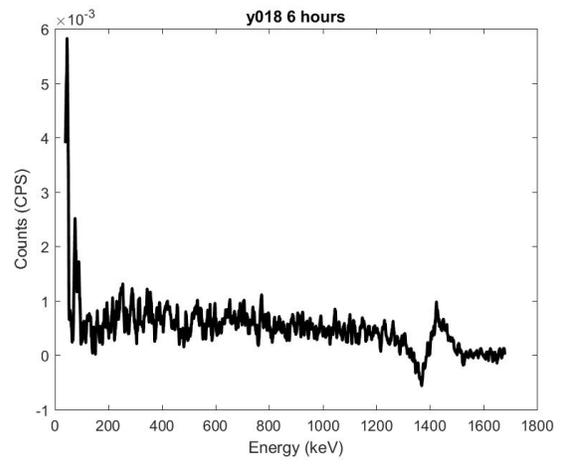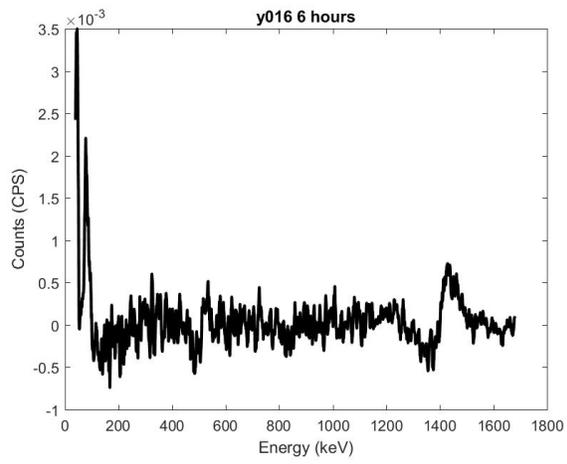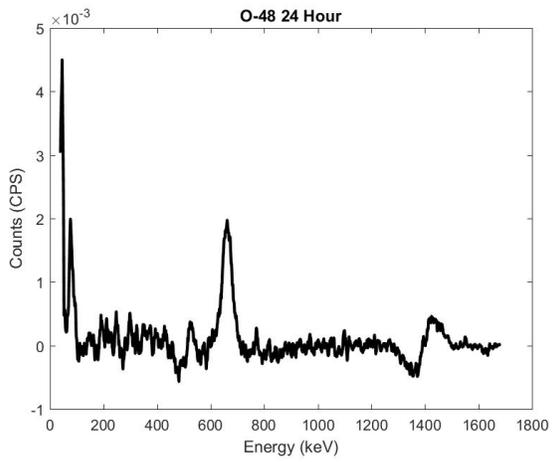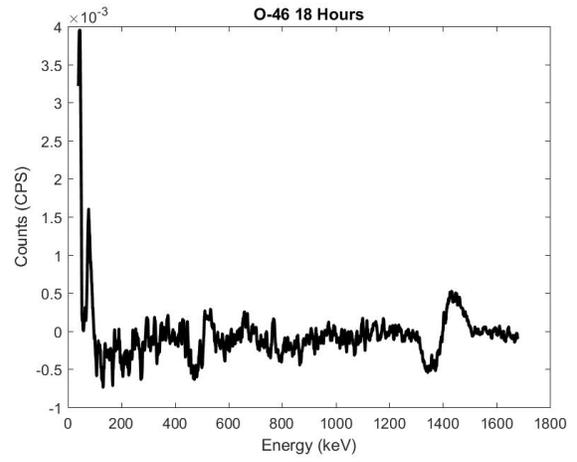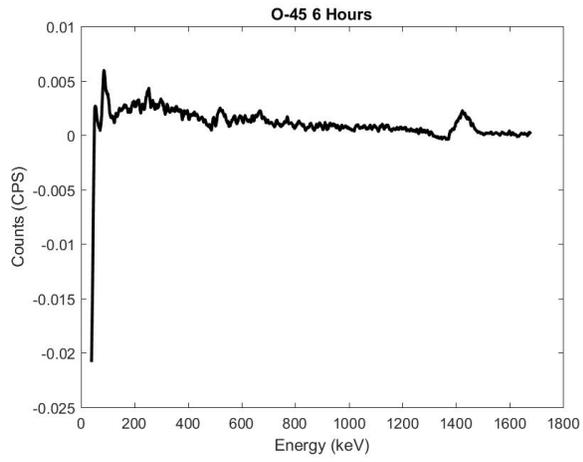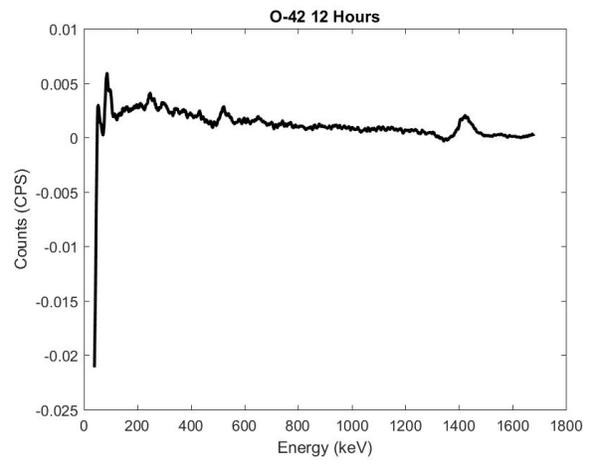
4. Hair Graphs (23) : Background Removed

O-50 24 Hours
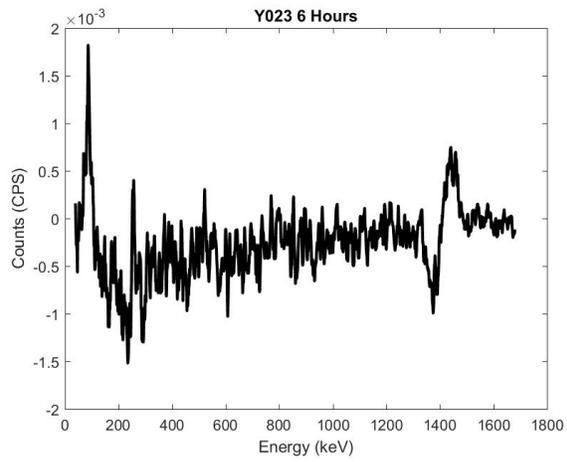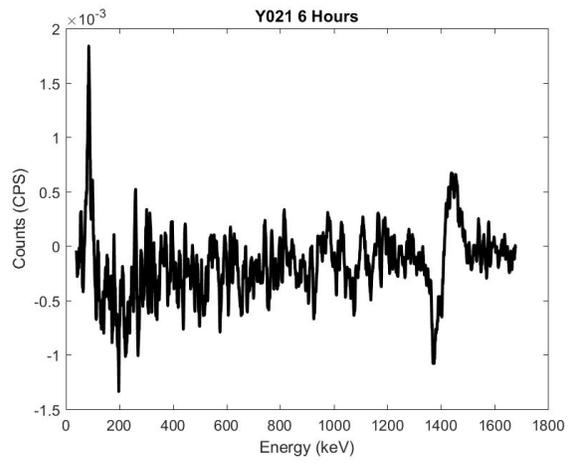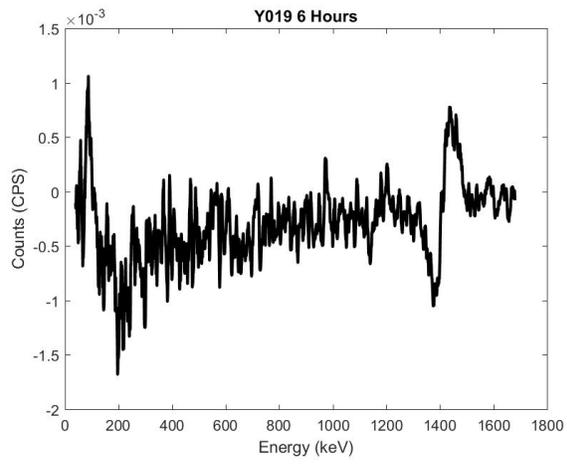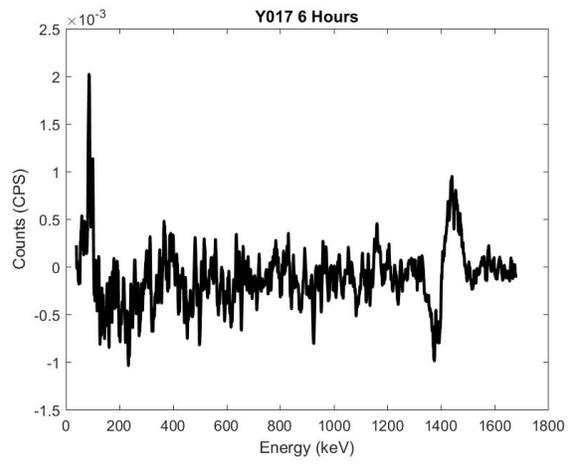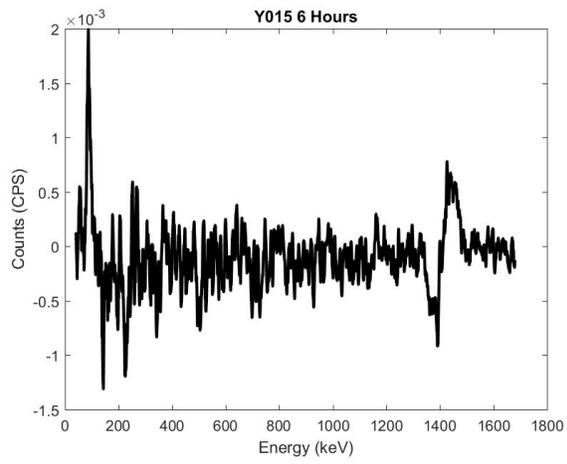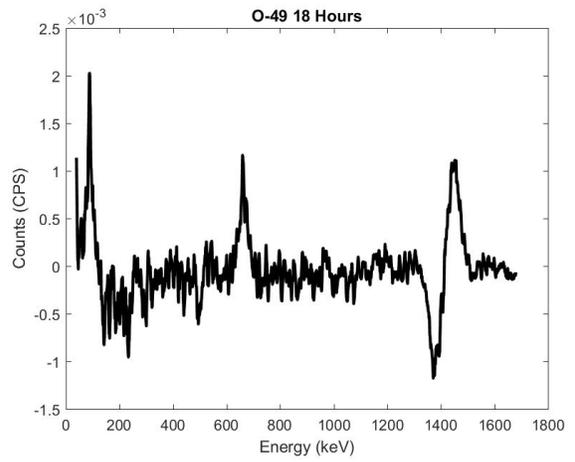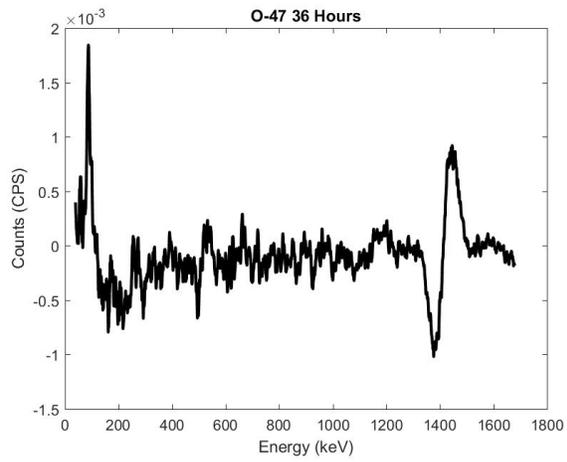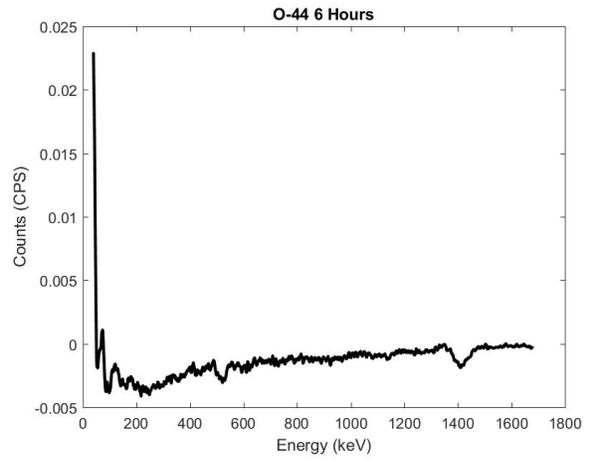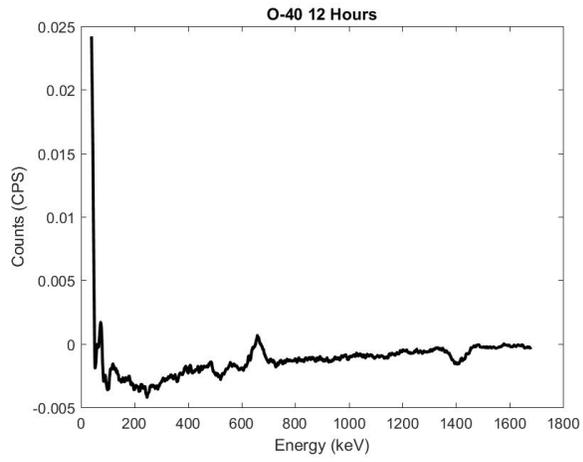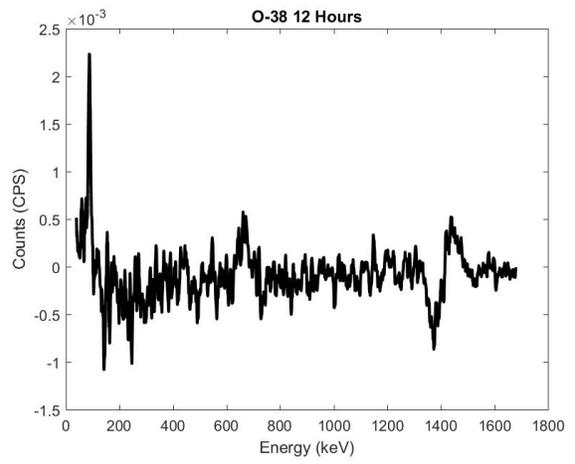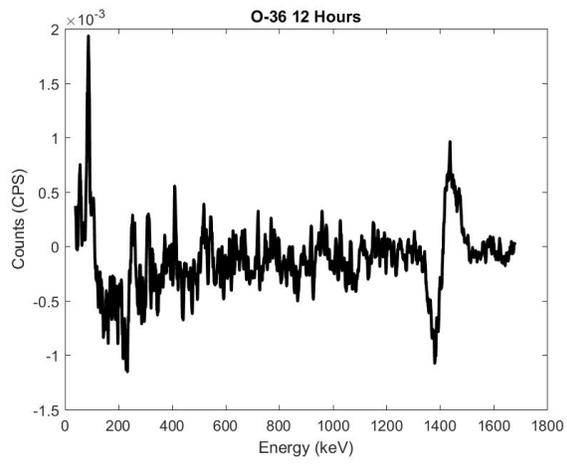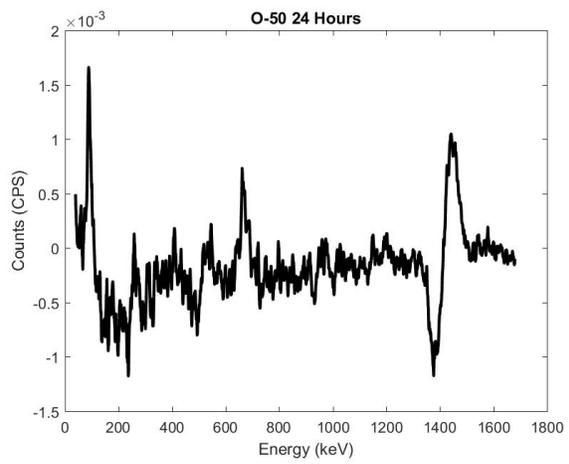
C. MATLAB Code

1. Background Removal (backsub.m)

```
%Background Removal Tool - Taylor Trottier - Jan 2018
```

```
%This program will hopefully remove background from all the files
%Currently runs on all csvs and will output to the same folder and
%create a concatenated csv of all datasets


function backsub
    time = 86400%This is changed based on the background file to be used


    %collect list of all csv files in folder
    files = dir(fullfile(pwd,'*.csv'));


    background = csvread('Back-T-24.csv',7,1); %Read csv background file, changed
        based on detector time etc
    background(:,2) = background(:,2)/time; % Conhorz the Counts into CPS
    %all calculations use background as counts/second
    energies = linspace(0,1680,1680)';
    %create 1680 interpolation points in a column vector spaced evenly
    %between 0 and 1680kev 1680 is a convenient and close highly composite
    %number. This will be the range selected for calculation
```

```matlab
interp = interp1(background(:,1),background(:,2),energies);
% interpolate values into a column vector at the specified


% generate a moving average for the 1% around the cesium-137 peak, this
% is approximately 7kev
interp = movmean(interp,7);


% after interpolation join together energies and interpolated values
iback = horzcat(energies,interp); %joins together energies and interpolated
    values


clear interp;


csvwrite("0_iback.csv",iback); % write the interpolated modified csv


number = numel(files);
%Generate an array to store the energies and all the graph values after
%fixing
fixed = zeros(length(energies),number); %array of all scans with background
    removed first column is energies
%set first row to energies
% zeros are initialized for speed later. This matrix isn't particularly
% large, but this is more general.


names=cell(1,number) ;%array of all names initialized with energy as its first
      value
% the name is saved for all for all csv files and stored here for
% output later
```

```
for i=1:number

    fname=files(i).name; %gets filename from file structure

    disp(fname);

    dtime = csvread(fname,2,1,[2,1,2,1]); %get scan runtime for calculating
        cps

    data = csvread(fname,7,1); %reads from ith file into data array in ith
        position

    data(:,2) = data(:,2)./dtime ; %calculates cps

    disp(fname)

    interp = interp1(data(:,1),data(:,2),energies); %interpolate datapoints
        for the file


    interp = movmean(interp,7); % average for the 7 values around the point


    idata = horzcat(energies,interp); % Generate interpolated arrays


    rdata = idata(:,2)-iback(:,2); %removed background data


    rary = horzcat(energies,rdata);


    fixed(:,i)=rdata; % add on removed background values to fixed


    names{i+1}=cellstr(fname); %sets column header in fixed (concatenated)
        array to the name of the file for that column
```

```
        %modify filename and write new csv values to modified array

        fname = "0_"+fname; % set filename

        csvwrite(fname,rary); % write csv file


        clear fname dtime data interp idata rdata rary ; % clear variables for
            next run through


    end
end
```

2. Standard Deviation Calculation from Peak Detection (calcpeak.m)

```
        % Calcpeak - Taylor Trottier - Jan 2018
%function finds peak then calculates fwhm and uses fwhm to calculate
%standard deviation and then collects all data larger than 2sigma and sums
%it to give a count range



function calcpeak
%Gets all files that have had the background removed
files = dir('0_*.csv');
%write to excel file with row labels
xlswrite('peaks.xlsx',["Sample","Peak","FWHM","STD","2StdSum"],1,"A1")


    for i = 1:numel(files)
        %get file name
```

```matlab
fname=files(i).name;

%get data

data = csvread(fname);

%split data for readability

energy = data(50:end,1);

measurements= data(50:end,2);

%get the index and value of the max measurements

[maxVal,index]=max(measurements);

%find fwhm (boolean vector for values above fwhm)

above = measurements >= maxVal/2;


%gets upper and lower indexes by finding the first and last values

%that go above and below fwhm

lowerIndex = find(above,1);

upperIndex = find(above,1,'last');


%calculates the fwhm d-energy

fwhm = energy(upperIndex) - energy(lowerIndex);


%using the gaussian relation between FWHM and StdDeviation

sigma = fwhm/(2*sqrt(2*log(2)));

centerIndex = find(measurements==max(measurements),1); %Find index of
    center

minEnergy = energy(centerIndex) - 2*sigma;

maxEnergy = energy(centerIndex) + 2*sigma;


%range of two std and then sums the values in that range

rtwosig = (energy>=minEnergy);

rtwosig = energy<=maxEnergy;
```

```matlab
        %actual sum of the region in the range of two standard deviations

        %if anyone actually reads this shoot me an email at

        %tgtrottier@wpi.edu or tgtrottier@gmail.com

        %double the value to account for the thin disk approximation

        %divide by 0.23 for detector efficiency

        twosig = 2*sum(measurements(rtwosig))/.2;


        %writes to file and displays the sum and

        disp(fname);

        disp(twosig);

        xlswrite('peaks.xlsx',[string(fname(3:end-4)),energy(index),fwhm,sigma,
            twosig],1,strcat('A',int2str(i+1)));
    end


end
```

3. Graph Making Function (makegraph.m)

```matlab
        %Makegraph - Taylor Trottier - Jan 2018
%creates a graph for every sample that has had its background removed


function makegraph
    %collect list of all csv files in folder
    files = dir('0_*.csv');


    %for all files with bg removed
    for i = 1:numel(files)
```

```matlab
%open new figure

figures=figure;

%get file name

fname=files(i).name;

%read in data

data = csvread(fname);

%plot data above ~50kev as data below this is unreliable


plot(data(50:end,1),data(50:end,2),'LineWidth',2,'Color','Black');

%creates a title from the filename

title(fname(3:end-4));


%labels the axes

xlabel('Energy (keV)');

ylabel('Counts (CPS)');

%prints to the console so I know its Running

disp((fname(3:end-4)));

saveas(figures,strcat(fname(1:end-4),'.jpg'));

close(figures);


    end
end
```

4. Calculation of Exponential Distribution

```matlab
%Find Cumulative Distribution Function - Taylor Trottier - Feb 2018
%Also Find Exponential; Distribution and use it to calculate 50% 75% and 99%
%case
```

```matlab
function expfit

    cdffig=figure;

    %read peaks to extract the normalized cps

    ncps = sort(xlsread('peaks.xlsx','F2:F9'));


    %size of dataset for calculation of step

    n=size(ncps,1);


    %calculate the step value for the CDF

    % p_plot is the probability step for plotting

    p_plot = ((1:n))' ./ n;


    %plot step function of probability

    p1=stairs([0;ncps;10],[0;p_plot;1],'k-');

    xlim([0,6]);

    hold on;

    title('Cumulative Probability Distribution of Fecal Data');

    xlabel('CPS/g');

    ylabel('Cum. Prob. (x)');


    %actual p we need to subtract a half to have our fit hit the center of

    %the step instead of the tops

    p = ((1:n)-0.5)'./n;


    %fitting the results to 1-e^(-lambda*x) which should give us a fit to

    %the cumulative probability and returns lambda

    fitResult = fit(ncps,p,fittype('1-exp(-lambda*x)'),'StartPoint',1.2);

    lambda = fitResult.lambda;
```

```matlab
%define the plot for the exponential cdf
p2=plot ((0:0.05:6),1-exp(-lambda*(0:0.05:6)));


%creates the legend p1 is stair p2 is fit location is set to avoid
%graph conflict
legend([p1,p2],'CDF', ['Exponential Fit:' num2str(lambda)],'Location','
    southeast');
%saves and closes the image
saveas(cdffig,'CDF.jpg');
close(cdffig);
%To Do; Create PDF Figure as well
%    pdffig = figure;
%    epdf = exppdf(ncps,lambda);
%    x = 0:.1:6;
%    plot(ncps,epdf);
%    title("Exponential Probability Distribution Function")
%    xlabel('CPS/g');
%    ylabel('P(x)');


end
```

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