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APPLICATION OF MOBILE APNEA SYSTEM TO CHARACTERIZATION OF TRU WASTE AT DOE SITES

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ABSTRACT

A trailer-borne Active Passive Neutron Examination and Assay nondestructive analysis system is being used in support of US Department of Energy transuranic waste characterization needed for the Waste Isolation Pilot Plant. This system can be relocated to a site requiring NDA for TRU and be operational in less than a week. In the passive mode, APNEA employs a high efficiency 4π neutron detector to measure autocorrelated neutrons emerging from 55-gallon TRU waste drums. In the active mode, the same neutron detector, plus a 14 MeV neutron generator are used to measure the thermal neutron induced fission rate of fissionable materials in the drums. By combination with isotopic ratio information, for example, from gamma ray spectroscopy, these active and passive neutron measurements yield assays for the TRU content of the drums. Both assay modes are needed for characterization of TRU waste –the passive assay is more accurate but the higher sensitivity of the active assay is needed to attain the minimum detection limit required for WIPP waste characterization. APNEA also employs a ^{252}Cf-neutron source to determine the waste type of the unknown drum, independently of prior knowledge. Waste heterogeniety effects are reduced by assay analyses using spatially dependent neutron-detection efficiencies and spatially dependent thermal neutron fluxes to match the measured waste drum. This APNEA system has been characterized using waste drum surrogates representing waste types from metals through sludge. It has participated and passed the Performance Demonstration Program (PDP) through cycle 5 and has been certified by participation in Carlsbad Area Office and Environmental Protection Agency audits.

INTRODUCTION

Containers of TRansUranic (TRU) waste to be disposed at the Waste Isolation Pilot Plant (WIPP) are subjected to Non-Destructive Analysis (NDA) with exacting measurement quality requirements (1). Often, when the quantity of waste is not large, it is more effective to bring a certified NDA system to the waste than it is to develop and certify a system on-site. Since the transportable system will be reused, more investment may be made in the transportable system than could be justified for a single use. In other instances, at sites where the number of drums to assay is large, a transportable system may be used to augment fixed installation NDA systems. A transportable, state-of-the-art neutron NDA system has been developed (2,3), which has the capability to measure two properties of 55 gallon drums: 1) the amount of spontaneous fission occurring in the drum and 2) the amount of thermal neutron fissionable material in the drum. These two properties are combined with isotopic ratio information from either prior knowledge or gamma spectroscopy to determine the TRU content of the drums. The transportable neutron NDA system, called APNEA (Active Passive Neutron Examination and Assay) was recently used (4) at the Nevada Test Site (NTS) to perform the WIPP-required NDA on 156 drums containing glove box waste from Lawrence Livermore National Laboratory. Isotopic ratio information from gamma spectroscopy was provided by another state-of-the art transportable

NDA system, the Waste Inspection Tomography system (WIT).(5) Many of the results shown here are from the work at NTS.

TECHNOLOGY EMPLOYED

The transportable APNEA (see Figure 1) is based on a prototype, fixed-installation APNEA developed (6) at ORNL, which was itself based on original work (7) at LANL on the PAN (Passive Active Neutron) system. In the PASSIVE mode, APNEA uses a 4π neutron detector and neutron auto-correlation to measure the rate of spontaneous fission in the drum. In the ACTIVE mode, the same neutron detector is used with time-dependent thermal neutrons originating from a sealed tube neutron generator to measure the fissionable material content of drums. A unique APNEA feature is a method (2) called External Matrix Probe (EMP) for determining the matrix characteristics of the unknown drum, without depending on drum records. Also, to reduce the effects of drum heterogeniety, APNEA uses strategic placement of neutron detector ^{3}He tubes, detailed system characterization and a special analysis method to determine the spatial distribution (image) of TRU in 54 volume elements (voxels). This image analysis is used for both the PASSIVE and ACTIVE assay measurements. For purposes of quality assurance and to enable method improvement, the transportable APNEA acquires and records data in the "list" mode (3) – the time and detection element of each neutron detection is recorded with a time resolution of about 3 microseconds. This information, stored on CD-ROM for each waste drum, may be examined in detail to assess suspected problems. If improved analysis methods are developed, or the surrogate database is updated, all the data are available for reanalysis.

Neutron Detector

The APNEA neutron detector (Figure 2) consists of 79 two-inch diameter ^{3}He proportional counters, ranging from 36- to 48- inches long. To reduce dead time effects, each detector has its own preamplifier, amplifier and discriminator. The detectors are surrounded by polyethylene moderator and constructed in nineteen assemblies. Each assembly is surrounded by cadmium, which absorbs thermal neutrons, so thermal neutrons that are incident on the assemblies are not detected. To be detected, a neutron must enter the assembly with energy above about 1 eV, and be moderated to thermal energy within the assembly so that the ^{3}He counters can detect them efficiently. The assemblies surround a chamber containing a drum turntable. To provide positional sensitivity, some assemblies are oriented with horizontal- and others oriented with vertical- axes. The assemblies are surrounded by a neutron reflector of graphite, which is surrounded by polyethylene shielding. One side of the chamber can be accessed for drum loading by opening a motorized chamber door. For use in the ACTIVE measurement, a sealed tube generator of 14 MeV neutrons (a Zetatron), surrounded by lead is embedded in one chamber wall. The Zetatron can be accessed for maintenance via a second motorized shield door. Neutron monitor detectors (one inch diameter ^{3}He) for thermal neutron flux determination are located in the chamber and two more one inch detectors for monitoring Zetatron output are located in the shield door. Each of the nine one inch diameter ^{3}He monitors, labeled T1, T2, U, V, W, X1, X2, X3, and Y, also have their own analog electronics.

Figure 1. Photograph of APNEA trailer on leaving its home base in Pocatello, ID, for NTS. This transportable system can be relocated to a new site and be operational within a week.

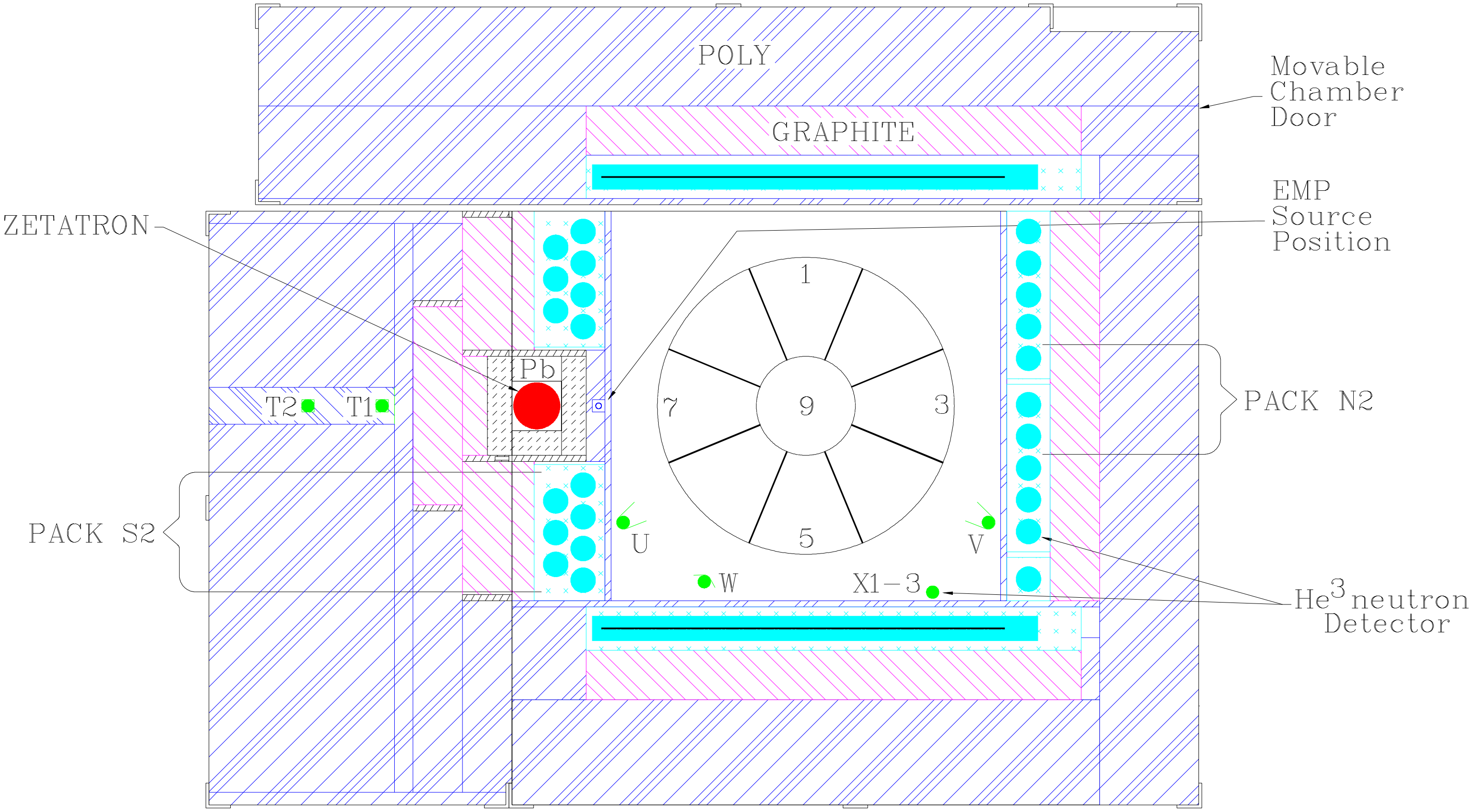


Figure 2. Cross section of APNEA detector, showing ^{3}He detectors (shaded), Zetatron (shaded), and one layer of 55-gallon drum voxels. The label, PACK N2 indicates the three ^{3}He detectors that compose detector pack North 2. Pack South 2 is composed of the seven ^{3}He tubes shown end-on at the lower left. U, W, X1-3 and V denote six ^{3}He neutron flux monitors inside the chamber. One additional flux monitor, Y, located at the top of the chamber is not shown.

Thermal neutrons inside the detector assemblies continue to scatter until they 1) escape the moderator and are absorbed by the cadmium wrap, 2) are captured by the moderator materials or 3) react with the ^{3}He, causing a detection. The thermal neutron population in the detector assembly decays approximately exponentially, with a time constant of about 50 microseconds. It is important that the thermal neutron die-away is slower in the waste drum cavity than in the detector assembly.

Passive Measurement

The APNEA PASSIVE measurement determines the amount of spontaneously fissioning material in a waste drum, using the neutron autocorrelation method(a) to separate spontaneous fission events from neutron background. In the APNEA neutron autocorrelation method, any neutron that is detected in the detector assembly is used to start a time gate, about 50 microseconds long, and any additional neutrons detected during the gate are said to be autocorrelated. The time gate and autocorrelation counts are created from the APNEA list mode data via software. Since fission events usually produce several neutrons simultaneously, the probability that fission will produce one or more autocorrelations is relatively high. Background from single neutron events can produce accidental autocorrelations, but this effect can be measured (or calculated) and subtracted. In the APNEA case, accidental autocorrelations are measured concurrently with the signal measurement. Spontaneous fission from any source, such as ^{240}Pu, ^{238}U or ^{252}Cf is detected by autocorrelation, but the APNEA system calibration is done for ^{240}Pu. Consequently, the PASSIVE measurement result is called equivalent ^{240}Pu (Eq240Pu) which is the amount of ^{240}Pu which would produce the same autocorrelation response as all the spontaneously fissioning material in the waste drum. Eq240Pu is converted into the amounts of isotopes present in the drum using isotope ratios from gamma spectroscopy together with calculated ^{240}Pu equivalencies for each isotope.

Active Measurement

The APNEA ACTIVE measurement determines the amount of thermal neutron fissionable material in a drum by irradiation of the drum with neutrons and detecting neutrons produced by the fission process. Fission neutrons are distinguished from the irradiating source neutrons by timing of the detection process and specially designed detectors. The Zetatron neutron source produces neutrons in intense bursts, about five microseconds long, at repetition rates up to 100 per second. The energetic (14 MeV) neutrons produced by the generator are scattered and slowed down to thermal energy by the materials of the APNEA chamber walls and the waste drum materials. Neutron thermalization is complete in a few microseconds, after which, there are no fast neutrons from the source until the next generator burst. Upon reaching thermal energy, the neutrons in the waste drum continue to scatter with no average change in energy until they 1) escape the drum or 2) are absorbed by the materials in the drum, or 3) create nuclear fission in a thermally fissionable material, such as ^{239}Pu or ^{235}U. Thermal neutrons that escape the drum may be returned to the drum by scattering in the APNEA chamber walls, which are covered with a layer of polyethylene, or they may be absorbed by cadmium outside of the polyethylene layer. The thermal neutron population in the drum decays approximately exponentially, with a time constant of about 200 microseconds. This time dependent population of thermal neutrons produces fast neutrons, which may be detected by the special detector assemblies, insensitive to thermal neutrons that surround the drum.

Fast neutrons from each generator burst flood the waste drum and the neutron detector assemblies. Initially, the generator neutrons cause many counts in the detector assemblies, but these counts disappear after a few hundred microseconds. Since the thermal neutrons in the APNEA drum cavity die-away slower than in the detector assemblies, thermal neutron fissions continue to occur in the waste drum after the generator neutron signal has disappeared from the detector assemblies. Some of the fast neutrons from these fissions penetrate the cadmium wrap of the detector assemblies and are detected. By selecting detections that occur after the generator signal has died away, fission neutrons are distinguished from generator neutrons. In practice, to increase the signal, detections are registered before the detections of generator neutrons have disappeared completely and a measured background, called the fast component is subtracted.

The fast component has a time dependence that depends on the detector assembly properties, but its amplitude depends on the neutron scattering and absorption properties of all the nearby materials, including the waste drum materials. For each assay, the fast component amplitude is determined by measurement of the detector signals at early times after the generator burst, where the generator neutrons totally dominate over any fission neutrons. A universal fast component for each detector pack, independent of surrogate, is normalized to this amplitude and used for background subtraction.

Waste Matrix Effects

The matrix materials of a waste drum, their geometric distribution and the distribution of fissioning material have a significant effect on both the PASSIVE and ACTIVE neutron measurements. Depending on the matrix, both the neutron detection efficiency and the irradiating thermal neutron flux can be strongly dependent on position within the waste drum. To handle these effects, APNEA uses information from detailed system characterization with a number of surrogate drums having different matrix characteristics. The same surrogates are used for ACTIVE and PASSIVE characterization. Vertical positioning tubes in the surrogates are used for placement of either a weak (^{252}Cf) spontaneous fission source for measuring efficiency or placement of small thermal neutron detectors to measure the irradiating flux. Using separate hardware arrangements, efficiency and thermal neutron irradiating flux are measured in each tube (3 to 6, depending on surrogate) at six heights. The efficiency and flux data are accumulated into eight azimuthal intervals. Each radial position, height, and azimuthal position are identified by a position index. The relative neutron-detection-efficiency is measured in each of the 79 neutron detectors. Measurements of the flux as a function of azimuthal position with the turntable rotating are made possible, even with detector electrical connections, by limiting the rotation to one turn and repeating the one-turn measurements several times. The flux values are determined in ten time intervals following the neutron generator pulse. The relative efficiency and flux (see Figures 3 and 4 for examples) are measured in each surrogate waste drum. The efficiency is a strong function of position within the drum and detector location. The flux depends strongly on position within the drum and its time dependence is similar throughout the drum. Both efficiency and flux depend strongly on the drum matrix materials. These relative efficiencies and fluxes are converted to absolute efficiencies and fluxes by calibration with a particular surrogate drum containing National Institute of Standards and Technology traceable sources of Weapons Grade Pu (WG Pu). Using interpolation in radius, the efficiencies and fluxes are mapped to 54 voxels formed from a core and eight annular segments at six heights.

External Matrix Probe

APNEA uses a unique method, called External Matrix Probe (EMP) (2), to select efficiency and flux surrogates to use for a waste drum. No prior information about the waste matrix is used in this method. The PASSIVE assay mode uses efficiencies determined from efficiency surrogates and the ACTIVE mode employs these same efficiencies plus thermal neutron fluxes measured for other surrogates. To determine the surrogates to use for efficiency, a strong ^{252}Cf source of neutrons is placed inside the chamber containing the drum (see Figure 2.) and the neutron count rates are measured. These count rates are characteristic of the neutron scattering and moderation of the waste drum. The same EMP measurement has been made for each of the surrogate drums. The best efficiency surrogate is the one whose neutron scattering and moderation, as measured by the detector pack count rates, is nearest that of the waste drum. A second surrogate is selected whose measured neutronic properties are such that the waste drum properties lie between those of the best and the second surrogate. APNEA uses, for PASSIVE analysis of waste drums, the interpolated pack efficiencies, between best and second surrogate, for detection of neutrons emitted in each voxel. In this way, a set of simultaneous equations for pack count rates as a function of drum azimuthal orientation can be solved to determine the Eq240Pu in each of 54 voxels of the waste drum. The drum assay for Eq240Pu is the sum, over voxel, of the Eq240Pu components.

For determination of the surrogates to use for thermal neutron flux required for ACTIVE analysis, several thermal neutron detectors are positioned in the APNEA chamber, outside the waste drum, to measure the neutron flux produced by the generator. The same EMP measurement has been made for each of the surrogate drums. The best flux surrogate is the one whose neutron flux distribution, measured outside of the drum, is nearest that of the waste drum. In addition, a second surrogate is selected whose measured flux distributions are such that the waste drum properties lie between those of the best and the second surrogate. APNEA uses, for analysis of waste drums, the interpolated fluxes, between best and second surrogate, in each voxel. The surrogate selection process is automatically done by the APNEA analysis software. When combined with the voxel dependent efficiencies, a set of simultaneous equations for detector count rates as a function of drum azimuthal orientation can be solved to determine the Eq239Pu in each of 54 voxels of the waste drum. The drum assay for Eq239Pu is the sum, over voxel, of the Eq239Pu components.

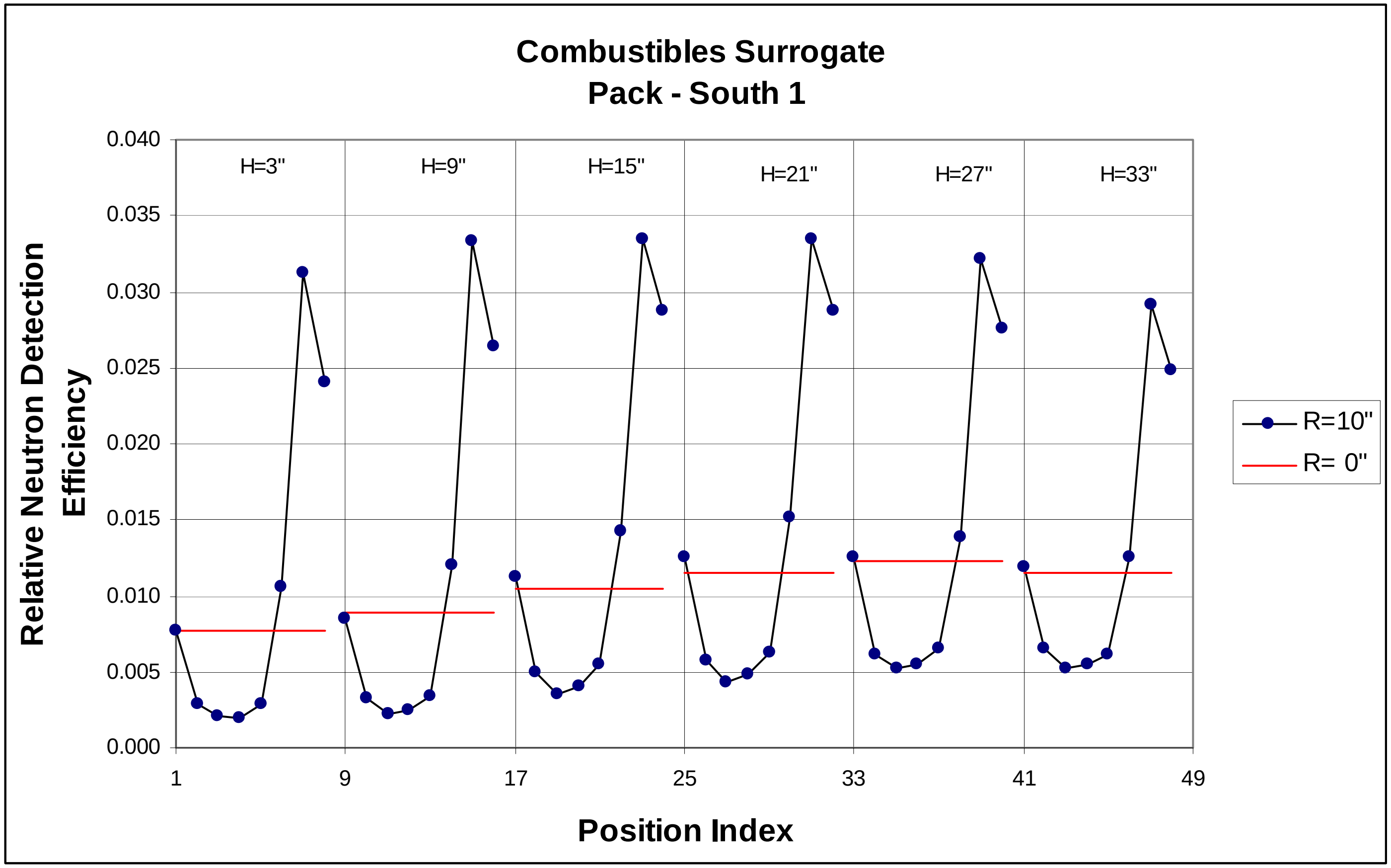


Figure 3. Example of neutron detection efficiency characterization data. This figure shows the efficiency of one grouping (one of 12 packs) of detectors for the combustibles surrogate drum. These efficiencies were measured by positioning a ^{252}Cf source of neutrons at six different heights (H) and two different radii (R) inside the surrogate and rotating the surrogate. The neutron count data were summed over eight azimuthal intervals. For example, position index values from 17 through 24 correspond to the source positioned at 15 inches above the base of the surrogate. The average value for the source positioned at R=0 is plotted as a horizontal line. Statistical uncertainties are less than the size of the data points. The APNEA characterization database includes from 1224 to 2952 such pack efficiency values for each surrogate (13 so far), depending on the number of radial positions available.

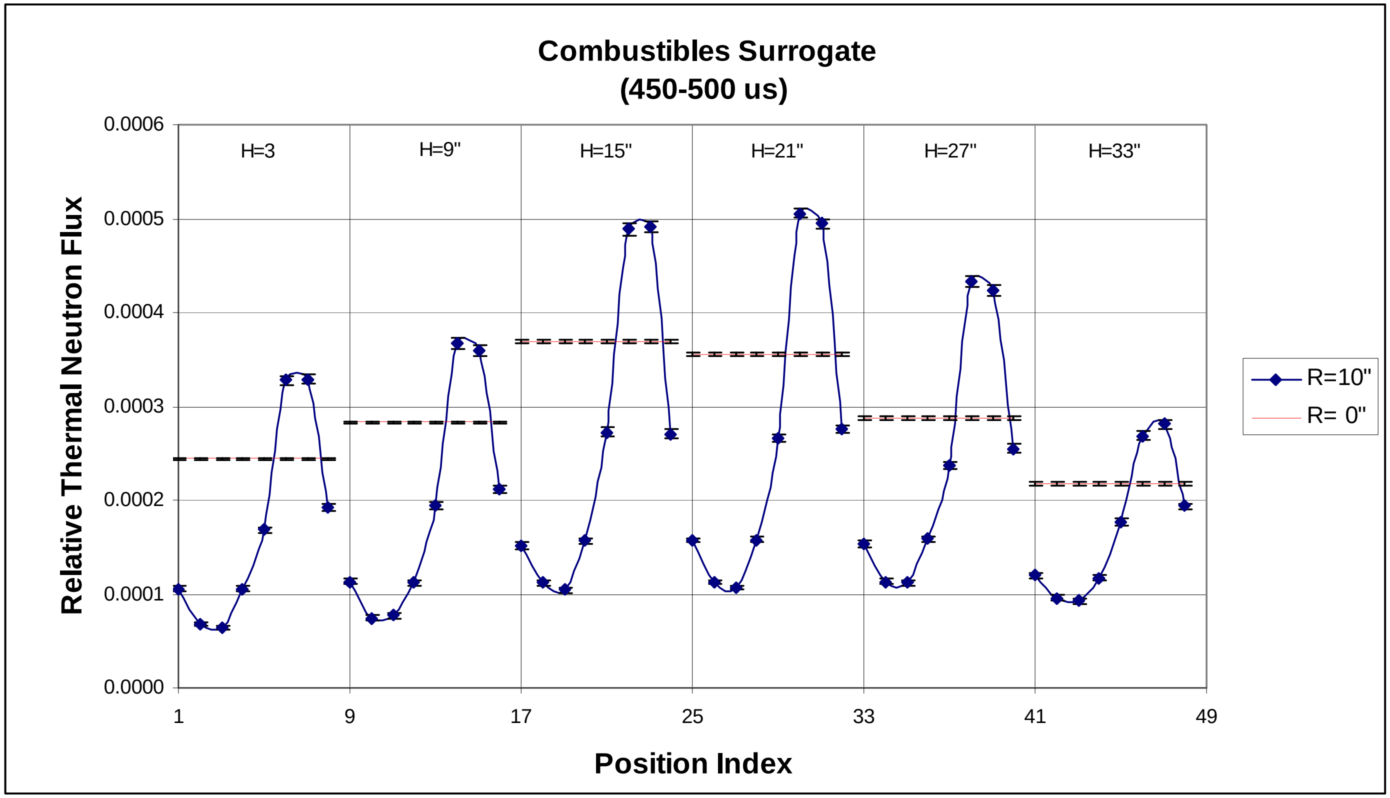


Figure 4. Example of thermal neutron flux characterization data. This figure shows fluxes in the time interval of 450 to 500 microseconds after the Zetatron burst inside the combustibles surrogate drum. These fluxes were measured by positioning a small thermal neutron detector at six different heights (H) and two different radii (R) inside the surrogate and rotating the surrogate. The neutron count data were summed over eight azimuthal and ten time intervals. For example, position index values from 17 through 24 correspond to the detector at 15 inches above the base of the surrogate. The average value for the detector positioned at R=0 is plotted as a horizontal line. Statistical uncertainties are indicated in the figure. The APNEA characterization database includes from 1020 to 2460 such flux values for each surrogate (13 so far), depending on the number of radial positions available.

Solution Method

Solution of the simultaneous equations is done using an iterative, weighted least squares approach. This solution depends on the counting statistics for the waste drum, which are propagated through the analysis to the assay answer. Additional measured components of random uncertainty are added later to the count statistics component. Therefore, the APNEA assay answer consists of the total amounts of Eq240Pu and Eq239Pu and the standard deviations of these total amounts. When the amount of either Eq240Pu or Eq239Pu is small, the uncertainties introduced by the 54-voxel-solution process are large. In this case, to reduce analysis uncertainties, a uniform distribution of material is used. So, there are two PASSIVE and two ACTIVE assay answers from APNEA: Uniform Eq240Pu, Imaged Eq240Pu, Uniform Eq239Pu and Imaged Eq239Pu. The choice between Uniform and Imaged answers is made automatically by the APNEA analysis software using the reduced chi-squared goodness of fit parameter.

APNEA Images

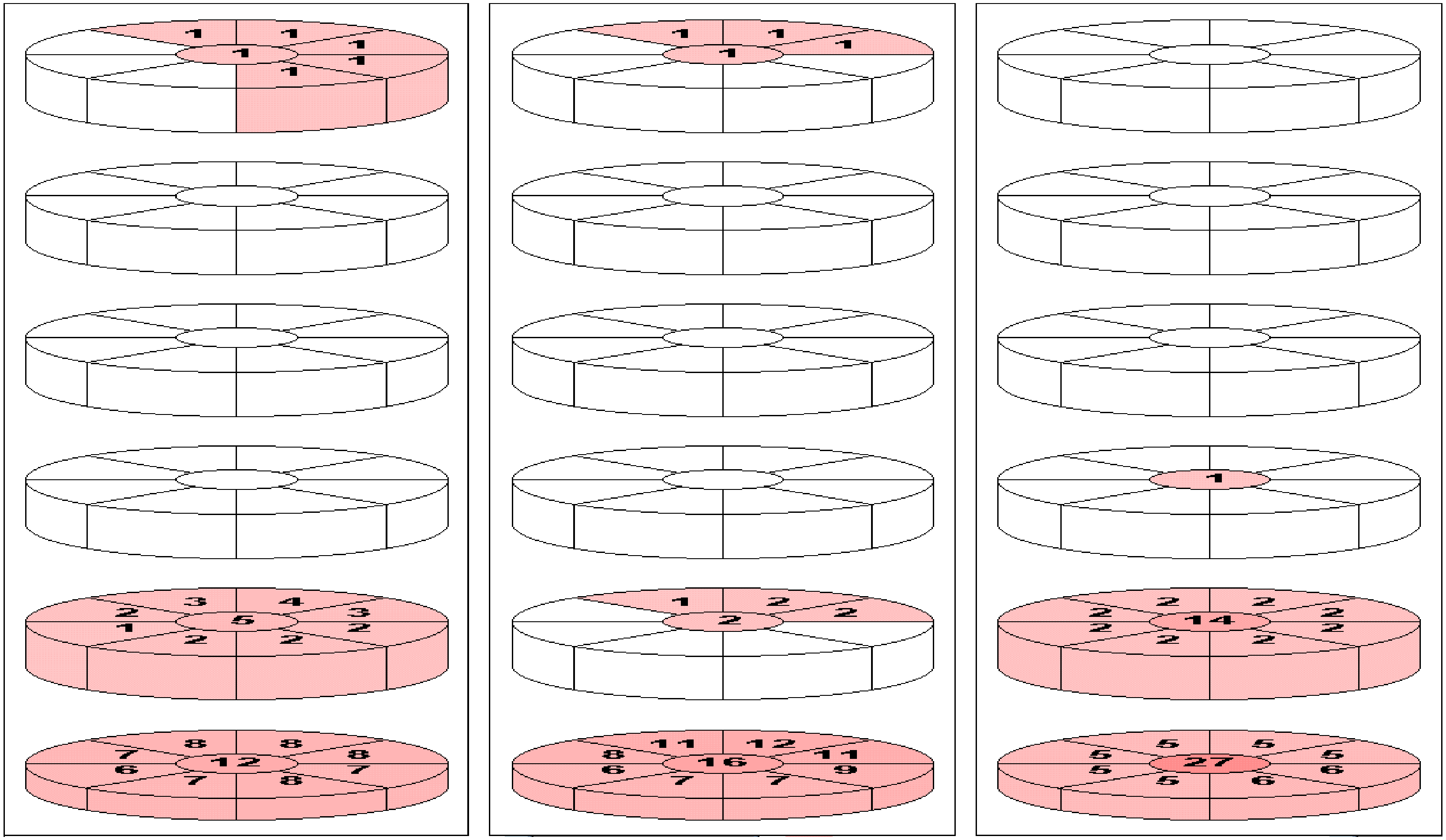
There are three drum images produced by the APNEA analysis software. In addition to the images created for the PASSIVE and ACTIVE assays, an image is created from the neutron counts without auto-correlation constraint in the PASSIVE acquisition mode. These unconstrained counts, called "singles" are caused by spontaneous fission, plus the neutrons arising from (α,n) reactions. The (α,n) component depends strongly on chemical composition and can be produced by ^{241}Am, so singles cannot ordinarily be used for assay, but its spatial distribution is likely to be the same as the fissioning components. Since the count statistics of singles is better than those of the correlated signals, the singles image is used as a starting image for the correlated image analysis. An example of the three images for an NTS waste drum is given in Figure 5.

Determination of TRU

The APNEA equivalent assay values are converted into TRU amounts using isotopic ratios to ^{239}Pu. This conversion is necessary because TRU is specified to be a sum of alpha activity, which is not directly measurable by NDA. The assay values are first converted to amounts of ^{238}Pu, ^{239}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{237}Np and other isotopes. Then, the known alpha decay properties are used to compute TRU. Isotopic ratios are sometimes known from process information, but, more often, they are measured by gamma spectroscopy on the actual waste drum

Data Acquisition

Data acquisition is automatically done with an interactive Windows NT controlling program (). The operator starts the process by using a bar code reader on the waste drum and activating the loader. A predefined sequence is then done: Load drum, start turntable, close chamber door, check interlocks, warm up Zetatron, make ACTIVE measurement, stop Zetatron, make EMP measurements at six source positions, make passive measurement, open chamber door, stop turntable, unload drum. During this sequence, data files are created by a data logger (3) and automatically transferred in the computing background to a hard drive. The entire process, excluding the time to manually archive data to CD, requires 23 minutes.



Singles Correlated Active

Figure 5. Illustration of ACTIVE and Passive images for an example NTS waste drum with measured TRU content of 11 grams of WGPu. The drum is shown exploded into 54 voxels. The image labeled "Singles" is from measurement of all neutron signals. The image labeled "Correlated" is from measurement of auto-correlated neutrons from spontaneous fission. The image labeled "ACTIVE" is from measurement of neutrons produced by thermal neutron fission. The numbers in each voxel indicate the percent of drum TRU in each voxel. In this case, the differences in the three images are attributed to statistical imperfections in the imaging process. Use of imaging improves the assay accuracy.

Operations at Nevada Test Site

APNEA was used to assay 156 waste drums at DOE's Nevada Test Site (NTS), as part of a TRUtech contract to do non-destructive examination, headspace gas analysis, gamma-spectroscopy and neutron assay. The TRUtech WIT facility was used for nondestructive examination by x-ray and for gamma spectrometric determination of isotopic ratios. The WIT capability for gamma assay was not used. Information about the characteristics of the waste to be measured was very limited, so it was difficult to predict Total Measurement Uncertainties[b] (TMU) before assay measurements were done. A significant amount of off-site work was required to refine the WIPP required estimates of TMU. In addition, because Pu standards were unavailable away from DOE sites, it was necessary to perform a number of quality-assurance verification measurements and Performance Demonstration Program (PDP) tests after arriving at NTS. PDP Cycles 4 and 5 (combustibles and sludge) were completed successfully. It should be noted that no APNEA characterization was done specifically for NTS waste. The existing surrogate database was used for system characterization. During and after the assay period the Carlsbad Area Office of DOE and later, EPA, conducted audits of TRUtech operations. Although it was expected that new issues would arise at the first field deployment, the large number of such issues and the effort required to resolve them was unexpected. Many of the issues resulted from the fact that the WIPP requirements were developed for DOE sites, rather than mobile contractors.

Results on NTS Waste Drums

The waste drums measured at NTS were very heterogeneous. Although all drums had been repackaged and were expected to be full, the net weights of waste ranged from 5 to 135 kg. The drum matrix heterogeniety indicated by this wide range of weights results in rather large TMU.

The criterion for acceptance of waste into WIPP is that the TRU concentration plus measurement uncertainty[c] be greater than 100 nCi/(g of waste). All drums assayed met this criterion. The measured TRU concentration for the NTS waste drums measured by APNEA is shown in Figure 6. Approximately 60% of the drums measured have TRU concentrations less than 15,000 nCi/g. The largest TRU concentration was 306,000 nCi/g. The TMU for fifteen of the drums assayed was excessively large (greater than about 100% for the 95% confidence interval). Drums with problem assays are not certified for WIPP. They may be re-measured with different technique, including longer assay time, or they may be opened and repackaged to remove assay problems, then re-measured. In most cases problem assays resulted from uncertainty in the gamma ray spectroscopy determined isotopic ratio of ^{241}Am to ^{239}Pu which is used in conversion of the neutron assay to TRU. Isotopic ratio uncertainty has been considerably improved by a new gamma-spectroscopy system (5) that has been developed by WIT.

Results for a random selection of fifteen NTS waste drums is shown in Table 1. The final assay result is TRU in nCi/g, together with its uncertainty. The relative precision and TMU for the PASSIVE and ACTIVE mode assays, Eq240Pu and Eq239Pu are also shown. In the table, precision and TMU are shown at one standard deviation. For small amounts of TRU, Eq240Pu precision is poor because of count statistics and the Eq240Pu TMU is large because of variability in the background. The precision of EQ239Pu is always good, but its TMU is large because of uncertainty in self-shielding and matrix absorption for NTS waste drums. This latter uncertainty was measured by the standard deviation of the ratio of ACTIVE to PASSIVE assay. The mode used for TRU determination, indicated by boldface type, was determined automatically to be that which results in the smallest TMU. This determination is closely related to the relative TMU for Eq240Pu and Eq239Pu, but conversion to TRU using isotopic ratios has an additional effect – see drum 14. As indicated in the table’s notes, one of the 15 drums has excessively large TMU on TRU, but the TMU for neutron assay is typical.

The criticality safety criterion for 55-gallon drums is that all drums have less than 200 Grams of Fissile material Equivalent to ^{239}Pu (FGE). Figure 7 shows the FGE values measured by APNEA for NTS waste drums. As for TRU, isotopic ratio information from gamma spectroscopy or prior knowledge is needed to convert neutron assay results into FGE. All drums measured were well below 200 FGE.

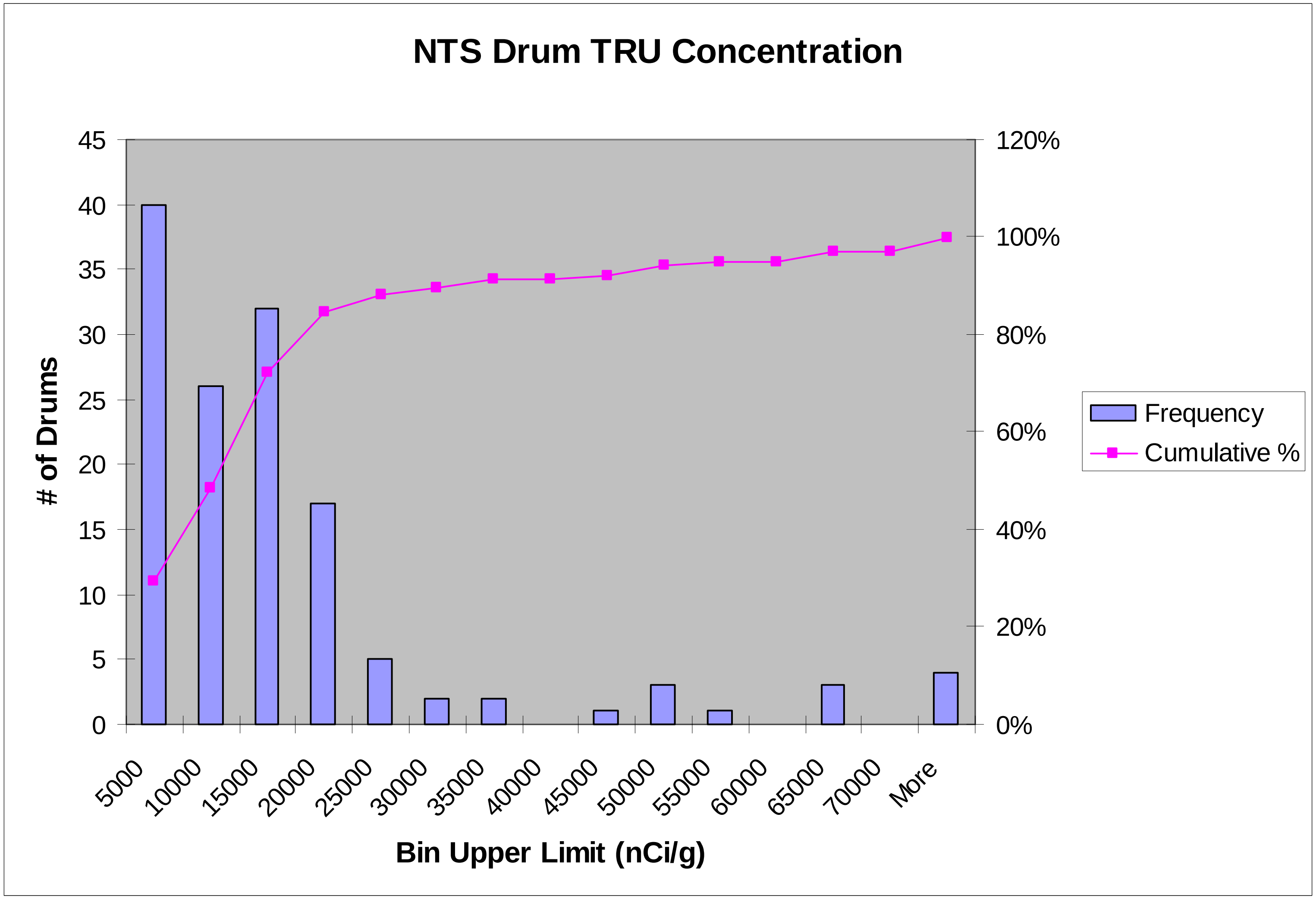


Figure 6. Distribution of measured TRU concentration in NTS drums of mixed glove box waste. PASSIVE or ACTIVE neutron assay by APNEA was used. To convert the neutron results to TRU, isotopic ratios from gamma spectroscopy were used.

Table 1. Results for 15 Randomly Selected Drums

Drum	Eq240Pu		Eq239Pu		TRU		
	Precision (Std.Dev.) (%)	TMU (Std.Dev.) (%)	Precision (Std.Dev.) (%)	TMU (Std.Dev.) (%)	Value (nCi/g)	Precision (Std.Dev.) (%)	TMU (Std.Dev.) (%)
1	18	48	**1**	**46**	1217	12	48
2	131	347	**2**	**50**	489	3	55
3	17	46	**1**	**45**	2478	7	53
4	17	45	**1**	**45**	19478	70	84*
5	**1**	**8**	1	44	36502	2	29
6	116	185	**2**	**46**	637	4	52
7	57	149	**1**	**48**	4458	15	51
8	**10**	**26**	1	56	1378	10	27
9	**3**	**10**	0	56	8697	3	10
10	167	455	2	**59**	977	3	63
11	**14**	**36**	1	56	1708	14	38
12	**17**	**44**	1	58	2121	17	45
13	**9**	**24**	1	56	3359	9	25
14	**25**	**66**	1	57	888	25	67
15	21	57	**1**	**65**	805	1	72

* This drum is not certified for WIPP because of large TMU. Note that the TMU of Eq239Pu is much smaller. The increase in relative TMU is because of uncertainty in the measured isotopic ratio of 241Am to 239Pu. The uncertainty in this isotopic ratio would be much less with the improved WIT gamma spectroscopy system.

SUMMARY

The transportable APNEA has been successfully applied for NDA of TRU waste drums for WIPP certification. The APNEA results were enhanced by the EMP method for selecting surrogates to use for neutron detection efficiency and thermal neutron flux and by the use of imaging analysis to reduce the effect of waste heterogeniety. Although about 10% of drums assays had unacceptably large Total Measurement Uncertainty, this was found to be mainly the result of uncertainty in gamma spectrometric determination of the isotopic ratios needed to convert neutron assay into isotopic amounts. This source of uncertainty has been reduced for future assays.

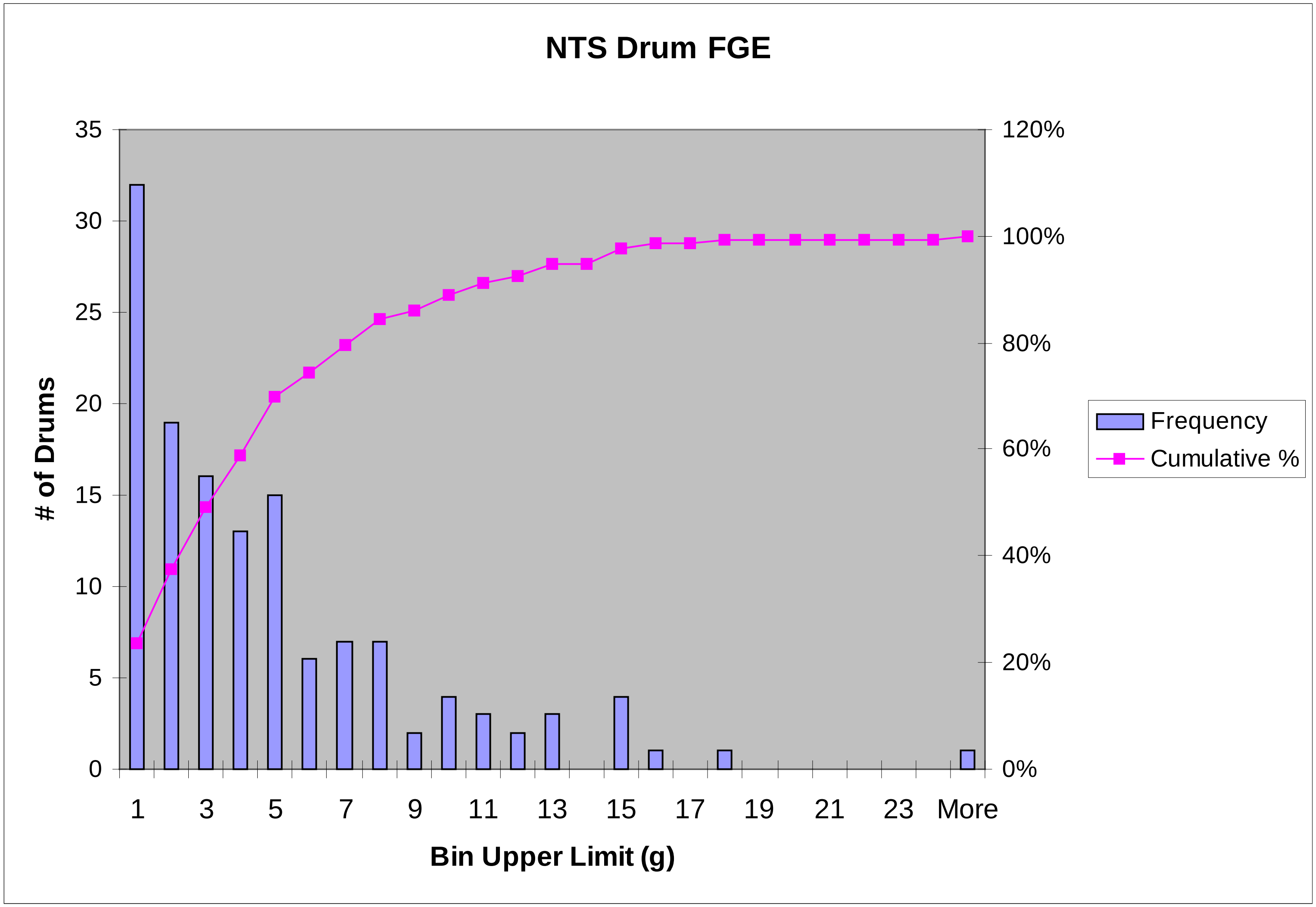


Figure 7. Measured Fissile Gram Equivalent (to ^{239}Pu) for NTS mixed glovebox waste. The largest measured FGE was 24.4 g.

ACKNOWLEDGEMENTS

Engineering design and construction of the transportable APNEA was done under the supervision of C.R. Smalley of Custom Manufacturing and Engineering (CME), St. Petersburg, FL. Field operations and data analysis were excellently carried out by the following CME personnel: J.A. Austin, P.S. Brown, D.A. Ehlers, W.S. Forshay, L. Godbee, and C.F. Weber.

FOOTNOTES

[a] In spontaneous fission, several fast neutrons are usually produced simultaneously, but background from the waste consists mostly of single neutron events. Fast neutrons are not detected directly by the APNEA thermal neutron detectors, the neutrons must first be moderated to thermal energy by scattering in the detector materials.

[b] Total Measurement Uncertainty is the estimate of the combined precision and accuracy of the measurement.

[c] The acceptance criterion quoted, from Revision 5 of DOE/WIPP-069,"Waste Acceptance Criteria for the Waste Isolation Pilot Plant" has been significantly changed in Revision 7.

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