INSTITUTE FOR ENERGY AND ENVIRONMENTAL RESEARCH

6935 Laurel Avenue, Suite 201
Takoma Park, MD 20912

Phone: (301) 270-5500
FAX: (301) 270-3029
e-mail: ieer@ieer.org
http://www.ieer.org

Memorandum

To: Vanessa Pierce, Executive Director, HEAL Utah
From: Arjun Makhijani
Subject: Savannah River Site Depleted Uranium Shipments to Utah
Date: February 16, 2010

You have asked me to analyze whether the U.S. Department of Energy's (DOE's) past and proposed disposal of Depleted Uranium (DU) from the Savannah River Site (SRS) at EnergySolutions' low level radioactive waste (LLRW) disposal facility in Clive, Utah, conform to the U.S. Nuclear Regulatory Commission's (NRC's) low-level radioactive waste (LLRW) disposal rule and to the Energy Solutions' Waste Acceptance Criteria (WAC). These are shipments of "Recycled DU," that is, DU that has been irradiated and therefore has traces of fission products as well as transuranic radionuclides such as various plutonium isotopes. [1]

As summarized below, I have concluded that neither the quantity nor the isotopic composition of the Recycled DU from the SRS meets the regulatory requirements for disposal as LLRW at the EnergySolutions site. My conclusions are summarized below. The bases for my conclusions are discussed in Attachment A (which presents my analysis of the DU disposal issue) and Attachment B (which focuses on the technetium-99 (Tc-99) concentrations in the waste drums and was prepared by Dr. Harry Chmelynski, who is a statistician).

As discussed in more detail in Attachments A and B, I have concluded that:

1. The disposal of such large amounts of DU as the DOE proposes to dispose of at the EnergySolutions site is not authorized by the NRC regulations that form the basis for the State of Utah's own regulatory program, nor has it been subjected to the required environmental analysis. Even a very expansive view of the history of the regulation would not allow concentrations of uranium-238 higher than 50 nanocuries per cubic centimeter (cc) or a total amount of uranium-238 in excess of 17 curies (about 51 metric tons). The total number of curies of uranium in the 33,000 DU drums at SRS is 300 times (or more) greater than the maximum amount arguably envisioned under the low-level waste rule. The concentration is more than an order of magnitude greater than 50 nanocuries per cc. As you know, the NRC acknowledges that large

[1] Recycled DU is distinct isotopically from "Virgin DU," which is DU that has been generated by the enrichment of uranium ore that has not been irradiated. The isotopic composition of Virgin DU consists of natural uranium isotopes and the radionuclides in their decay chains, none of which are in Tables 1 or 2 of 10 CFR 61.55(a). Recycled DU generally contains radionuclides listed in Table 1 or Table 2 or both; this is the case with the SRS recycled DU under consideration here. The distinction is central to my conclusion in paragraph 2 below but immaterial for my conclusion in paragraphs 1 and 3.

amounts of DU were not covered by the low-level waste rule and is currently engaged in a process of determining what kinds of restrictions are appropriate for large amounts of depleted uranium. This rulemaking, however, has not been completed.

2. Disposal of recycled DU in any amount as Class A waste is not permitted. This is because classification as Class A waste under 10 CFR 61.55(a)(6) requires that the waste not contain any of the radionuclides listed in Tables 1 or 2 of LLRW disposal rule. In fact, the recycled DU from SRS that is proposed to be disposed of as Class A waste at the Clive, Utah, site contains radionuclides from both Table 1 and Table 2, including plutonium isotopes, iodone-129, technetium-99, strontium-90, and cesium-137.[2] As a result, recycled DU from SRS does not meet the regulatory definition of Class A waste, and disposal of recycled DU as Class A waste in any amount at any concentration is not permitted under federal low-level waste regulations. Therefore, the proposed disposal of recycled DU at the EnergySolutions site violates the low-level waste rule, independent of arguments related to the quantity of uranium involved.

3. Quite apart from the uranium content of the SRS waste, it is virtually certain that the technetium-99 content of many of the drums exceeds the Class A limit of 0.3 curies per cubic meter. Since only 33 samples were taken from 33,000 drums of recycled DU and the drums are not segregated between those meeting the Class A limit for Tc-99 and those above it, none of the drums can be disposed of as Class A waste for this reason alone. The DOE's claim that Class A limits for Table 1 and 2 radionuclides are met is based on a misleading interpretation of even the few samples that were taken. A properly conducted statistical analysis shows that it is more than 99 percent likely that a large number of drums would violate the Class A limit of 0.3 curies per cubic meter for Tc-99. Such an analysis is presented in Attachment B.

In sum, there are three different ways in which the recycled DU from SRS is not permitted to be disposed of as Class A waste at the Clive, Utah site.

In view of the three findings above and the past disposal of recycled depleted uranium at the EnergySolutions site, I have also concluded that neither the Utah Division of Radiation Control nor the NRC has been exercising due oversight over the low-level waste disposal process. Finally, it should be noted that the analysis in this report shows that the DOE has also not respected federal low-level waste rules in the process of sending its wastes to a commercial site covered by NRC regulations. Finally, if recycled uranium, whether depleted or not, has been disposed of at the EnergySolutions facility in Utah in the past, this too would violate the low-level waste regulation. This is a matter that should be carefully investigated by the State of Utah and by the NRC.

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[2] Profile Record 2009 (EnergySolutions, *Radioactive Waste Profile Record, EPA ID# SC1890008989, Waste Stream ID-9021-33. Waste Stream Name SRS DUO, Rev. 0, 11/16/2008, Shipped on December 8, 2009*) and an attachment to the Profile Record 2009: Parkinson 2002 (K.S. Parkinson, *Depleted Uranium Oxide Sampling Results*, Interoffice Memorandum, to S. A. Williams and D.L. McWhorter, (NMM-ETS-2002-00184, Revision 0, Tracking number: 100049, D/A: DOE/ADM 17-17.a), Westinghouse Savannah River Company, Savannah River Site, November 4, 2002).

Attachment A

Analysis of Low-level Waste Regulations and Disposal of Recycled Depleted Uranium[3]

Arjun Makhijani

The Nuclear Regulatory Commission's low-level waste regulation is published in the *Code of Federal Regulations* at 10 CFR Part 61. Section 61.55 specifies the concentrations of a variety of radionuclides that constitute the system of classification of waste into Class A, B, C, and Greater than Class C. However, not all radionuclides and types of waste are listed in 10 CFR 61.55. Specifically, the rule does not cover large amounts of depleted uranium, such as those from enrichment plants. In addition, it does not cover waste, such as recycled DU, that consists of combinations of radionuclides that are listed in Tables 1 or 2 of 10 C.F.R. 61.55 and radionuclides that are not listed in either table..

1. **Large Amounts of DU**

Small amounts of DU have been allowed to be disposed of as Class A waste under 10 CFR 61.55(a)(6) which states that all low-level waste not explicitly mentioned in Tables 1 and 2 constitute Class A waste. However, in October 2005, the NRC explicitly recognized that DU in large amounts was not covered by the rule. This clarification was needed because large amounts of DU were not considered waste at the time that the final rule was promulgated in 1982.

The NRC has begun its rulemaking process with initial explorations of whether large amounts of DU could be classified as Class A waste, with the additional requirement of a site-specific analysis prior to disposal. The NRC staff prepared a paper presenting calculations for hypothetical wet and dry sites and held workshops in Bethesda, Maryland, and Salt Lake City, Utah, in September 2009, on this and related topics. The Department of Energy participated in these workshops.

The NRC's presentations during these workshops explicitly recognized that only small amounts of DU at low concentrations were analyzed in developing the LLRW disposal rule and that disposal of higher concentrations and amounts were not covered by the low-level waste rule as it stands at present. Larry Camper of the NRC, who provided the overview, stated the context as follows:

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[3] The physical, chemical, and radiological properties determined from analyses of these samples are provided in the EnergySolutions Radioactive Waste Profile Record and a 2002 memorandum prepared by SRS: EnergySolutions, *Radioactive Waste Profile Record, EPA ID# SC1890008989, Waste Stream ID-9021-33. Waste Stream Name SRS DUO, Rev. 0, 11/16/2008, Shipped on December 8, 2009*. Hereafter Profile Record 2009. The form was filled out by the DOE and the information regarding the results of radionuclide sampling attached to it was provided in an attachment by the Savannah River Site. We note that the file signature page on this document [pdf p.5], is dated 11-23-09, and labeled ID-9021-32. The attachment is K.S. Parkinson, *Depleted Uranium Oxide Sampling Results*, Interoffice Memorandum, to S. A. Williams and D.L. McWhorter, (NMM-ETS-2002-00184, Revision 0, Tracking number: 100049, D/A: DOE/ADM 17-17.a), Westinghouse Savannah River Company, Savannah River Site, November 4, 2002. Hereafter Parkinson 2002.

> The Commission realized the uranium enrichment landscape was drastically changing. So when during the hearings for the LES facilities, Interveners filed contentions regarding the impacts from DU disposal. The Commission directed staff to evaluate these impacts separate from the hearing process. The Commission stressed in their order to the NRC staff to consider the quantities of DU at issue and noted that ***these large quantities were outside the bounds of the evaluation conducted in the Part 61 rulemaking in the early 1980s***.[4]

Mr. Camper's statement makes it clear that the NRC has recognized that large amounts of DU are not covered by the low-level waste rule. That is one of the reasons that the NRC is pursuing a modification of 10 CFR 61.55(a).

The NRC staff also provided further detail on what was analyzed during the process of rule-making. This is important since it provides a guide for the amounts and types of uranium-containing waste that might reasonably be disposed of prior to a modification of the rule covering large amounts of such waste. According to Mr. Camper of the NRC staff:

> Approximately six metric tons of DU were assumed to be Class A in the draft Environmental Impact Statement. A draft concentration limit of 0.05 microcuries per cubic centimeter was determined. This draft concentration limit was not adopted in the final Environmental Impact Statement based on the Part 61 FEIS conclusion that "the types of uranium bearing waste typically being disposed of by NRC licensees do not present a sufficient hazard to warrant limitation on the concentration of this naturally-occurring material."
>
> However, the specific activity of depleted uranium is 0.5 microcuries per cubic centimeter and now the landscape for waste stream generation is changing. So clearly NRC is entering new territory not envisioned when Part 61 was initially developed.[5]

Slides presented at the workshop by Dr. David Esh, the principal NRC staff author of the technical paper, further stated:[6]

> Depleted Uranium Disposal:
> Problem Context
> • Large quantities of uranium were not evaluated in the EIS for 10 CFR Part 61
> – 17 Ci of ^{238}U (in 1 million m^3 of waste)
> – 3 Ci of ^{235}U

Dr. Esh elaborated on this slide as follows:

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[4] *Public Workshop on Unique Waste Streams: Depleted Uranium,* Nuclear Regulatory Commission, Bethesda, Maryland, September 2, 2009, Official Transcript of Proceedings, on the Web at http://www.nrc.gov/about-nrc/regulatory/rulemaking/potential-rulemaking/uw-streams/workshop-1-transcripts-day1.pdf, p. 25. Hereafter NRC Transcript September 2, 2009, emphasis added.

[5] NRC Transcript September 2, 2009, pp. 23-24.

[6] David Esh, *Site-Specific Performance Assessment and NRC Depleted Uranium Technical Analysis Overview*, September 2009, Slide 14, on the Web at (in a file combined with other presentations) at http://www.nrc.gov/about-nrc/regulatory/rulemaking/potential-rulemaking/uw-streams/du-workshop-presentations.pdf.

> So the depleted uranium disposal, the problem context, large quantities of uranium were not evaluated in the EIS for the 10 CFR part 61. But uranium was evaluated. Basically they evaluated about 17 curies of uranium-238 and 3 curies of uranium-235. And that was in roughly one million cubic meters of waste. So that gives you an idea of quantity and concentration that they assessed.[7]

The above facts about the process of rulemaking for 10 CFR Part 61, as well as the final omission of uranium from the list of radionuclides in the rule, provide the context for the amounts and types of uranium-bearing waste that might be construed as being covered by the low-level waste rule. Even though uranium is not mentioned in 10 CFR 61.55 explicitly, the history of the rule provides a rationale for arguing that 17 curies of U-238 and 3 curies of U-235 could be disposed of under the rule if these amounts were below certain concentrations. Further, an average concentration of 17 picocuries per cc might be considered acceptable, since the draft considered 17 curies in a million cubic meters (which equals a trillion cubic centimeters). Since the Draft EIS of the low-level waste rule proposed a much higher limit on the concentration of DU, at 50,000 picocuries per cc (=50 nanocuries per cc = 0.05 microcuries per cc), this might be construed as a potential *upper limit* on the concentration of uranium in low-level waste that could arguably be disposed of under the present low-level waste rule.

No reading of recent NRC decisions or of the low-level waste rule as promulgated would lead to a conclusion that disposal of more than 17 curies of U-238, the dominant uranium isotope in DU, and 3 curies of U-235, is permitted. Since U-235 is only 0.2 percent to 0.3 percent of the mass of DU and its specific activity is about 7 times that of U-238, the 17 curies value for U-238 would automatically be the limiting amount if the uranium to be disposed of is depleted uranium.[8]

The amounts of DU involved violate the limits discussed above. Using the weighted average value of the DU concentration provided in the Profile Record (311 nCi/gram), and the lowest value of density of 2.5 grams/cc, each drum contains just over half a metric ton of DU, almost all of which would be U-238 (by mass). This amounts to about 0.16 curies of U-238 per 55-gallon drum. Hence the limit of 17 curies would be reached in about 105 drums. If we use a median value of density,[9] the value of 17 curies would in about 78 drums.

Seen another way, the 33,000 drums can be expected to contain about 5,300 curies or more of U-238. This is over 300 times more than the maximum amount covered by the draft EIS that was part of the process that created the existing rule.

The DOE shipment also violates the concentration limit by a large amount. At the lowest density, the typical DU concentration in a drum would be about 780 nanocuries per cc. A median concentration would be about 1,040 nanocuries per cc, corresponding to a density of 3.35 grams/cc.[10] Both these values are tens of thousands of times greater than the concentration of 17 picocuries per cc (0.017 nanocuries per cc) analyzed in the EIS. They are also about 16 to 21

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[7] NRC Transcript September 2, 2009, pp. 78-79.

[8] Seventeen curies of U-238 would weigh about 51 metric tons. As DU this would contain 0.1 to 0.15 metric tons of U-235, amounting to 0.2 to 0.3 curies (rounded) of U-235.

[9] Assumed here to be the geometric mean of the lowest and highest values provided.

[10] This value is the geometric mean of 2.5 and 4.5 grams per cc, the range of densities provided by the DOE in the shipment manifest.

times higher than the limit of 50 nanocuries per cc for U-238 proposed in the draft low-level waste EIS.

The NRC has formally and publicly stated that any amounts of DU containing U-238 in excess of 17 curies or concentrations greater than 50 nanocuries per cc were not covered by the environmental impact analysis done for the low-level waste rule. Utah's authority to regulate disposal of LLRW derives from its status as an Agreement State under the Atomic Energy Act. As an Agreement State, Utah has an obligation to establish a regulatory program that is "adequate to protect public health and safety" and "compatible with the Commission's program."[11] DU disposal was not even considered in the NRC's Final EIS for the LLRW disposal rule and there is no existing NRC regulation that governs disposal of DU in the concentrations and quantities contemplated by the DOE in this case. The NRC has only just taken the first steps in its rulemaking for disposal of large quantities and high concentrations of DU. It has not prepared a formal draft environmental analysis under the National Environmental Policy Act (NEPA) for public comment. At this point, the State of Utah has no basis for establishing permit conditions for disposal of the DU that would be "compatible" with the NRC's program. Compatibility is especially important here since the disposal of large amounts of DU or DU in high concentrations has significant implications beyond the boundaries of the State of Utah.

In sum, the disposal of large amounts of DU or DU concentrations greater than 50 nancocuies per cc as Class A waste is not authorized by the federal regulations that form the basis for the State of Utah's own regulatory program; nor has the NRC subjected it to the environmental analysis required under the National Environmental Protection Act.

2. Recycled Uranium

Recycled uranium in any amount cannot be disposed of as Class A waste. Specifically, 10 CFR 61.55(a)(4)states:

> Classification determined by short-lived radionuclides. If radioactive waste does not contain any of the radionuclides listed in Table 1, classification shall be determined based on the concentrations shown in Table 2. However, as specified in paragraph (a)(6) of this section, if radioactive waste does not contain any nuclides listed in either Table 1 or 2, it is Class A.

Further, 10 CFR 61.55(a)(6) states:

> Classification of wastes with radionuclides other than those listed in Tables 1 and 2. If radioactive waste does not contain any nuclides listed in either Table 1 or 2, it is Class A.

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[11] *Statement of Principles and Policy for the Agreement State Program; Policy Statement on Adequacy and Compatibility of Agreement State Programs*, Nuclear Regulatory Commission, September 3, 1997, one the web at http://www.nrc.gov/reading-rm/doc-collections/commission/policy/62fr46517.pdf. .

When the nuclear industry as well as the NRC staff argued (incorrectly as the Commission's decisions have shown) that pure DU even in large quantities could be disposed of as Class A waste under 10 CFR 61.55(a)(6), even they noted that the DU they were speaking about did not contain any radionuclides in Table 1 or Table 2 of 10 CFR 61.55(a). For instance, the NRC staff testimony stated:

> Q.7. Is Envirocare authorized to accept the type of radioactive waste that will be generated by the NEF [National Enrichment Facility]?
>
> A.7. (TJ, JP, DP) Yes. Envirocare, which is regulated by the State of Utah Department of Environmental Quality Division of Radiation Control, is licensed to accept Class A low-level radioactive waste. Staff Exhibit 36 at 2-32. The Commission, in its decision *Louisiana Energy Services, L.P.*, CLI-05-5, 61 NRC 22 (2005), determined that depleted uranium is low-level waste. As explained in our FEIS, for regulatory purposes low level radioactive waste is categorized in three classifications: Class A, B or C based on the concentration of certain long-lived radionuclides which are set forth in Tables 1 and 2 of 10 C.F.R. § 61.55. ***The regulation further provides, in § 61 .55(a)(6), that if radioactive waste does not contain any of the nuclides listed in those Tables, it is Class A.*** Depleted uranium consists mostly of long-lived isotopes of uranium, with small quantities of thorium-234 and protactinium-234. None of those isotopes is listed in Table 1 or 2. Accordingly, pursuant to 10 C.F.R. § 61 .55(a)(6), depleted uranium is considered Class A low level radioactive waste.[12]

As we have seen the Commission has recognized and the NRC Staff has accepted that, contrary to the NRC Staff view just quoted, large amounts of DU were not covered by the low-level waste regulation. But there has been no assertion that DU containing contaminants listed in Table 1 or Table 2, much less both, would be Class A waste under 10 CFR 61.55(a)(6).

The DU that has been shipped from SRS to Clive, Utah, contains radionuclides from Table 1 (Tc-99, transuranic alpha-emitting radionuclides, plutonium-241 and iodine-129).[13] In addition, some radionuclides listed in Table 1 were not even analyzed (carbon-14, niobium-94, and nickel-59 in activated metal) because they were expected to be present in "trace quantities only."[14] The SRS DU also contains radionuclides listed in Table 2, including strontium-90 and cesium-137. Two of the radionuclides in Table 2, cobalt-60 and nickel-63, were not analyzed for similar reasons. In the plain language of the paragraphs of the LLRW disposal rule cited above, recycled DU cannot be considered as Class A waste.

This analysis shows that depleted uranium waste containing any amounts of radionuclides listed in Table 1 or Table 2 of 10 CFR 61.55(a) cannot be disposed of as Class A waste. The SRS waste in question contains at least some of these radionuclides. This is apart from the question of the Class A limit for Tc-99, which is discussed in Attachment B.

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[12] *In the Matter of Louisiana Energy Services*, Closed Hearing, Publicly Available Version, Atomic Safety Licensing Board, Nuclear Regulatory Commission, October 27, 2007, (NRC ADAMS # ML053610160) pdf pp. 16-17. Emphasis added. An industry view can be found in the same proceedings. See the testimony of the Louisiana Energy Services of October 26, 2005, Closed Hearing, Publicly Available Version, (NRC ADAMS # ML053610166) pdf pp. 294-295.

[13] Parkinson 2002. See also Profile Record 2009.

[14] Parkinson 2002, table showing radionuclides not analyzed and text that follows the table. No page numbers.

What makes the shipments from SRS to EnergySolutions especially egregious is that the shipments are occurring as the Nuclear Regulatory Commission has acknowledged the need for, and is actively considering, restrictions on the disposal of large amounts DU as low-level waste.

Attachment B

Estimating the Number of Drums Exceeding the Utah's Class A limit for Technetium-99

Dr. Harry Chmelynski

Summary

The Department of Energy provided measurements of radionuclides and other data regarding drums of depleted uranium waste recently shipped from the Savannah River Site (SRS) to the EnergySolutions Class A radioactive waste disposal facility. This report addresses whether any of the drums might exceed Utah's Class A limit of 0.3 Ci/m^3 for technetium-99 (Tc-99).[15]

The DOE sampled only 33 drums of about 33,000 drums of depleted uranium oxide. The manifest declares that "all samples" meet the WAC, but this assurance is provided using a single, low point estimate for density of 2.66 grams/cc, without taking into account stated variation in density of 2.5 to 4.5 grams/cc. It is also misleading in that the uncertainty in the Tc-99 content of the drums is not addressed.

This statistical analysis shows that, based on the Tc-99 measurements and density data in the Profile Record, a large number of drums would exceed Utah's Class A limit for Tc-99 of 0.3 Ci/m^3, which is also the federal limit. Four different distributions of Tc-99 in the drums were analyzed. A triangular distribution for density, with the mode at the low value of 2.66 grams/cc, used by DOE, was used. This is rather conservative in the sense that other choices, such as a uniform distribution, would result in higher estimates of the number of drums that would violate the Tc-99 Class A limit.

The results of the statistical analysis of the number of drums exceeding the Class A limit are shown in Table S-1. This analysis shows a "consensus estimate" (in the statistical sense) [16] of the 99 percent confidence range for the number of drums exceeding the Tc-99 limit as 682 drums to 5,678 drums. The best estimate is 3,180 drums or almost 10 percent of the drums. The range of best estimates is 2,253 to 4,036 drums, depending on the distribution chosen for the Tc-99 measurements. All four distributions give a lower 99 percent confidence bound of more than 2,000 drums exceeding the Tc-99 Class A limit.

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[15] 10 CFR 61.55(a)(3)(i); *Classification and Characteristics of Low-Level Radioactive Waste*, R313-15-1008, http://www.rules.utah.gov/publicat/code/r313/r313-015.htm#T46; and *Bulk Waste Disposal and Treatment Facilities Waste Acceptance Criteria: (Includes Class A LLRW, Mixed Waste, and 11e.(2) Disposal Embankments)*, revision 7, http://www.energysolutions.com/alpha/license/BWF_WAC.pdf

[16] The consensus estimate is the arithmetic mean of the best estimates obtained from the four simulations of technetium-99 activity. Confidence intervals for the consensus estimate of the number of drums exceeding the Class A limit are derived using the t-distribution with three degrees of freedom.

Table S-1: Number of Drums Exceeding the Class A limit for Tc-99

Assumed Distribution	Best Estimate	95% Confidence Interval		99% Confidence Interval	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Uniform	2,253	2,162	2,345	2,131	2,371
Normal	2,667	2,572	2,764	2,544	2,796
Gamma	3,763	3,650	3,877	3,614	3,914
Lognormal	4,036	3,922	4,154	3,882	4,186
Consensus Estimate	3,180	1,819	4,541	682	5,678

1. Technical Approach

Information submitted by Savannah River Nuclear Solutions in the Radioactive Waste Profile Record for approximately 33,000 drums of depleted uranium trioxide (UO3) [17] is based on calculations that rely on the average and "maximum" specific activity values derived from a small sample of 33 drums (0.1 percent sample) multiplied by a rather low point estimate of a second uncertain quantity – the waste density. The uncertainty accompanying these calculations is not reported. This paper addresses the issue of uncertainty in the technetium-99 calculations through the use of Monte Carlo simulation models. The models simulate the activity in 33,000 drums containing waste with random specific activity from a variety of probability distributions and random density. A software add-in program for Microsoft Excel named Crystal Ball from Decisioneering, Inc., was used to perform the simulations.

Attachment 1 to Parkinson 2002 in the waste profile record submitted by Savannah River includes measurements of the specific activity of technetium-99 in 33 sampled drums shown in Table 1. The frequency distribution of the samples is shown in the histogram in Figure 1. The shape of this plot is subject to a variety of interpretations, with no clear pattern due to the relatively small sample size. Six types of probability distributions were selected as possible candidates for the sample values: uniform, triangular, normal, lognormal, gamma, and Pareto.

[17] The data are from Parkinson 2002 and Profile Record 2009.

Table 1: Technetium-99 Specific Activity Measurements Reported by DOE

Sample ID	Measurement nCi/g	Sample ID	Measurement nCi/g
1	44.2	18	64.7
2	57.5	19	16.1
3	21.2	20	14.9
4	33.3	21	27.2
5	15.7	22	8.1
6	19.1	23	15.7
7	18.5	24	9.0
8	24.5	25	93.8
9	90.2	26	92.7
10	79.7	27	32.5
11	89.8	28	55.3
12	79.7	29	53.8
13	37.5	30	88.5
14	75.3	31	93.7
15	34.2	32	54.3
16	74.2	33	73.0
17	41.4		

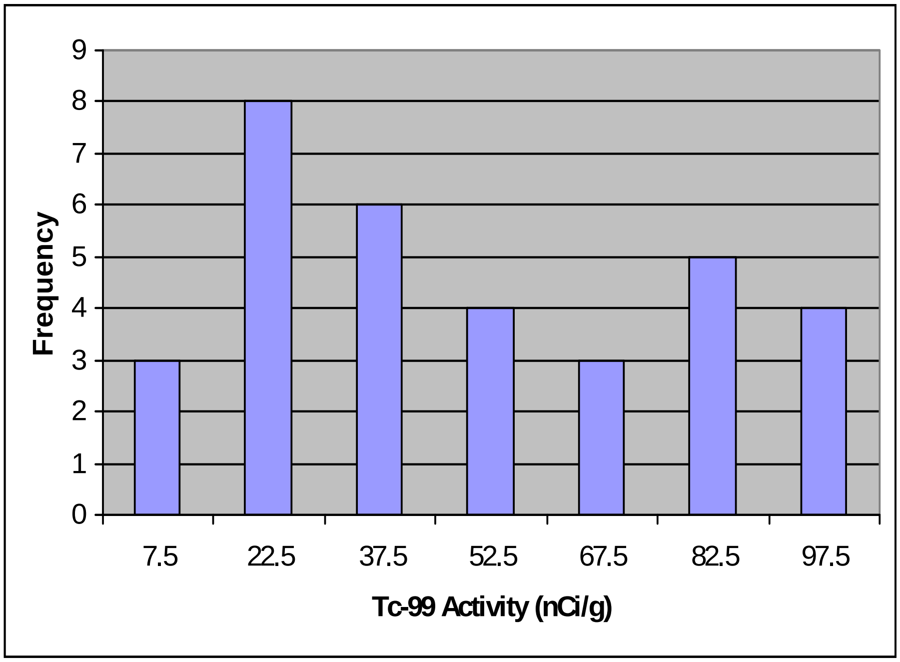

Figure 1: Histogram Showing the Frequency Distribution of the 33 Technetium-99 Sample Measurements

Crystal Ball was used to select the best fitting probability distributions. The Batch Fit function in Crystal Ball was applied in a step-wise procedure to find the best-fitting distributions for the samples in Figure 1. Crystal Ball provides a choice of three statistical measures of fit – Chi Squared; Kolmogorov-Smirnov; and Anderson-Darling – for selecting the best-fitting distribution from the set of candidate distributions. The three criteria were applied in a step-wise procedure to select the best fitting distributions for the technetium-99 samples.

In stage 1 of the step-wise procedure, the Chi Squared criterion in Crystal Ball produced the ranked results shown in Table 2. According to the Chi Squared criterion, the best-fitting probability distribution is the lognormal distribution. The correlation of the lognormal distribution with the technetium-99 sample measurements is shown in a scatter plot in Figure 2. Deviations of the sample values from the dashed regression line are an indication that the data may not fit a lognormal distribution. However, the correlation (R) is relatively high at 0.96.

Table 2: First Stage of Model Selection Using the Chi Squared Criterion

	Data Series:	**Technetium-99**
	Chi-squared p-value:	0.735758883
	Best fit:	Lognormal
1	Lognormal	0.735758883
2	Normal	0.658250763
3	Gamma	0.572406707
4	Uniform	0.513264961
5	Triangular	0.008261465
6	Pareto	7.28246E-06

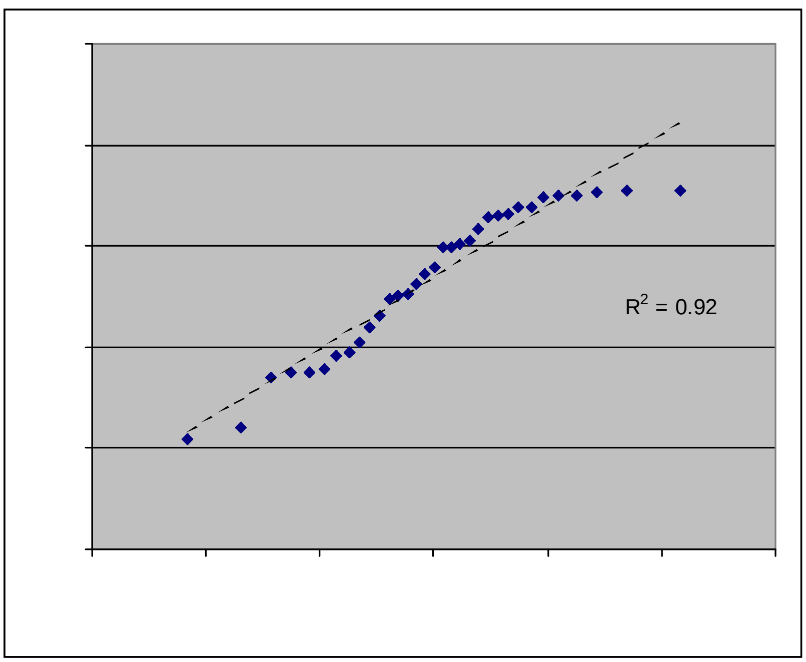

Figure 2: Correlation of the Lognormal Distribution with Technetium-99 Sample Measurements

In the second stage of the step-wise procedure, the Kolmogorov-Smirnov criterion was applied to select the best-fitting of the remaining five probability distributions. The results of the second stage are shown in Table 3. The Kolmogorov-Smirnov selection criterion selects the uniform distribution as the best fitting distribution. The correlation of the uniform distribution with technetium-99 sample measurements is shown in Figure 3. The uniform distribution appears to fit the data better than the lognormal, and the correlation is higher at 0.99. However, the uniform distribution has a fixed upper bound that is likely to be violated in a large population of 33,000 drums. For example, in a simulation using the best-fitting normal distribution (reported below), the maximum activity in 33,000 drums was found to be 52% higher than the maximum of the 33 sample values reported by the DOE, with a 99 percent confidence interval ranging from 36% to 85%.

Table 3: Second Stage of Model Selection Using the Kolmogorov-Smirnov Criterion

	Data Series:	**Technetium-99**
	Kolmogorov-Smirnov:	0.108194652
	Best fit:	Uniform
1	Uniform	0.108194652
2	Normal	0.123674853
3	Gamma	0.142254592
4	Triangular	0.200571689
5	Pareto	0.27120283

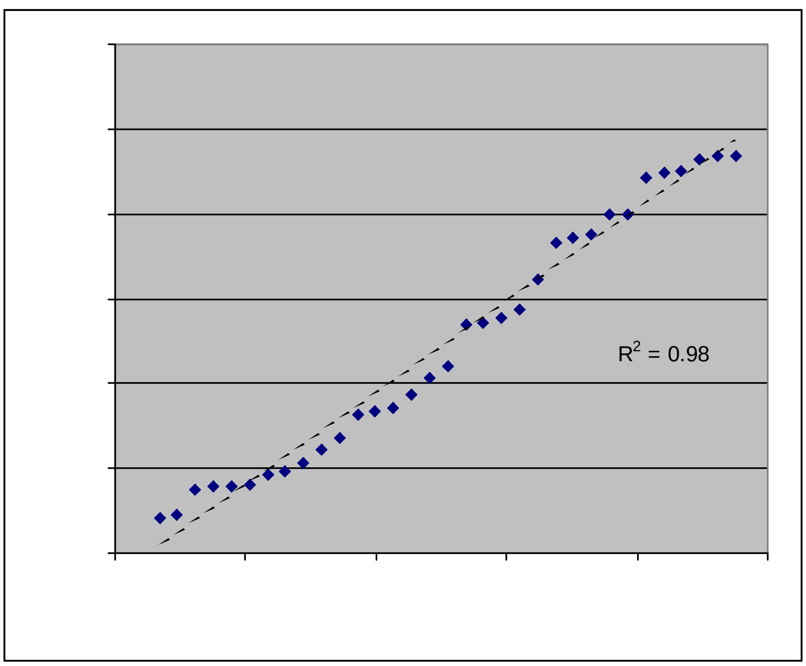

Figure 3: Correlation of the Uniform Distribution with Technetium-99 Sample Measurements

In the third stage of the step-wise selection procedure, the Anderson-Darling selection criterion was applied to select the best-fitting of the remaining four probability distributions. The results of the third stage are shown in Table 4. The Anderson-Darling criterion selects the gamma distribution as the best fitting distribution of the remaining four. The gamma distribution is similar to the lognormal distribution, with less weight in the upper tail. Since the normal distribution appears as the second best distribution in all three stages of the selection procedure, the normal distribution was also included in the simulation study as the wild card. The correlation of the normal distribution with technetium-99 sample measurements is shown in Figure 4. The plot is similar to the lognormal distribution plot in Figure 2, with approximately the same correlation.

Table 4: Third Stage of Model Selection Using the Anderson-Darling Criterion

	Data Series:	Technetium-99
	Anderson-Darling:	0.799840342
	Best fit:	Gamma
1	Gamma	0.799840342
2	Normal	0.942950967
3	Triangular	1.995038267
4	Pareto	4.342894632

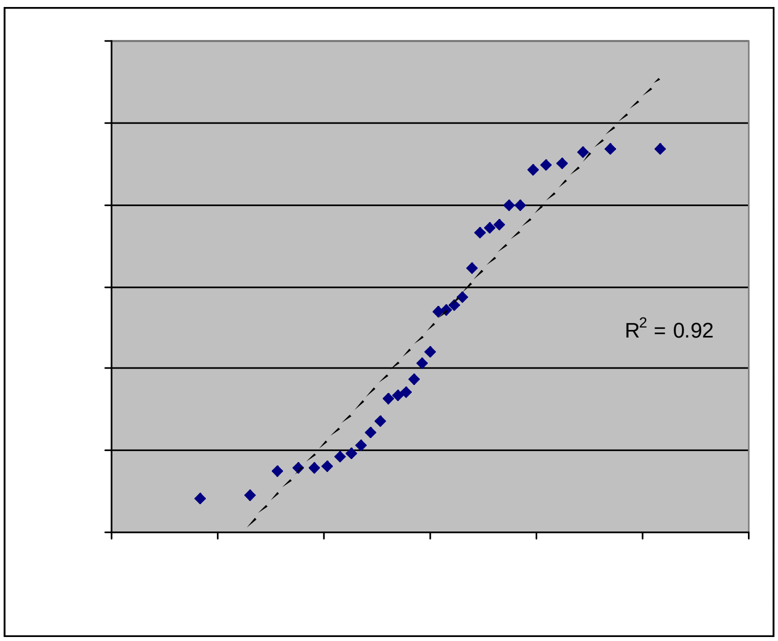

Figure 4: Correlation of the Normal Distribution with Technetium-99 Sample Measurements

Crystal Ball was used to estimate the parameters for the each of the four probability distributions selected above. The parameter estimates are shown in Table 5. Figure 5 contains frequency plots showing 5,000 simulated values from each of the four probability distributions selected by Crystal Ball. The best-fitting uniform distribution at the bottom of the figure has no tail extending beyond 100 nCi/g, but the other three probability distributions have no fixed upper bound, with non-negligible upper tails extending well above this value.

Table 5: Parameter Estimates for the Four Probability Distributions Selected for Simulation of Technetium-99 Specific Activity

Distribution	Parameter	Estimate
Uniform	Minimum	5.42
	Maximum	96.48
Normal	Mean	49.37
	Standard Deviation	29.26
Gamma	Location	7.24
	Scale	30.99
	Shape	1.36
Lognormal	Geometric Mean	39.52
	Geometric Standard Deviation	2.08

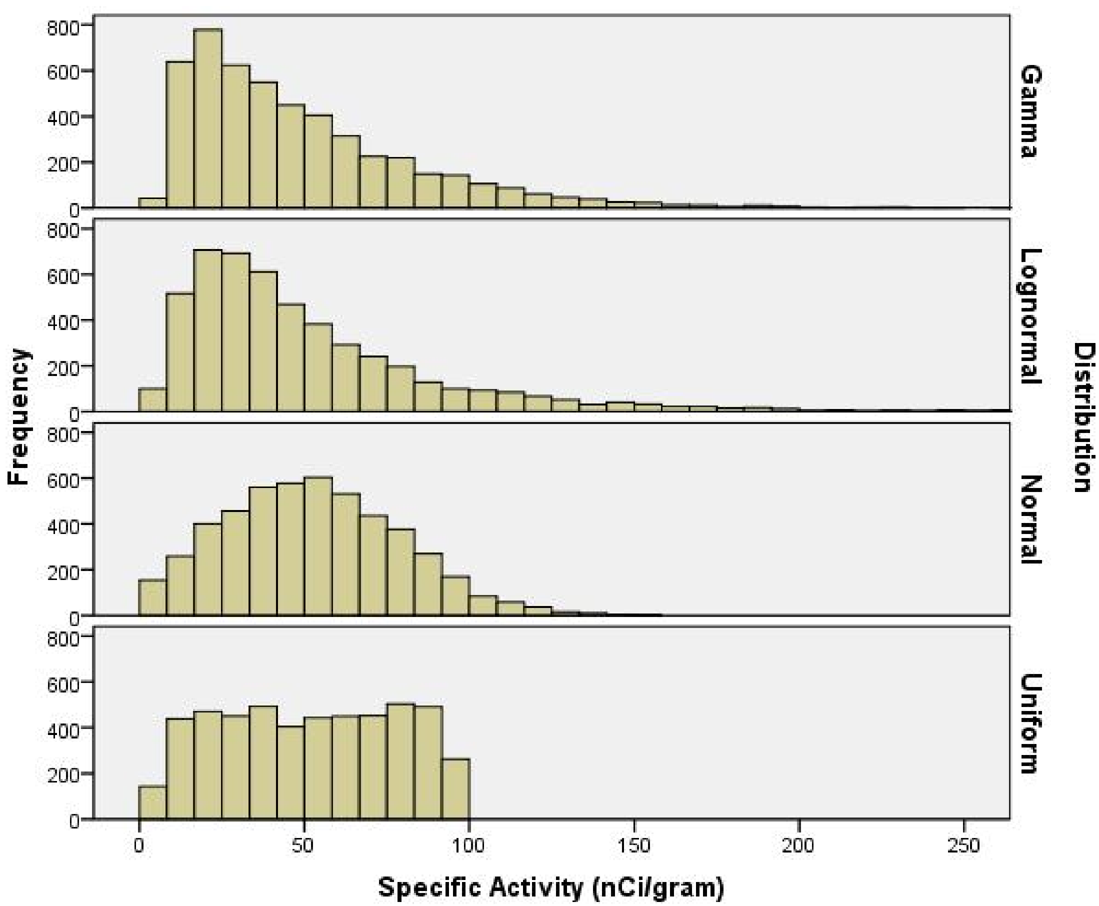

Figure 5: Comparison of the Four Probability Distributions Selected for Simulation of Technetium-99 Specific Activity

Part B.1 of the waste profile record submitted by Savannah River states that the density of the waste material ranges from 2.5 to 4.5 grams per cubic centimeter (g/cc). In the accompanying interoffice memo (Parkinson 2002), DOE states that the average and maximum technetium-99 drum activities are 0.1313 and 0.2495 curies per cubic meter (Ci/m^3), respectively. These values are consistent with an assumed density of 2.66 g/cc. However, it was stated that the density of the waste material may range from 2.5 to 4.5 g/cc. DOE has selected a density very near the lower end of this range. A triangular distribution was used to reflect the uncertainty in the density of the waste. The distribution selected for the waste density ranges from 2.5 to 4.5 g/cc with a most likely value (the mode) of 2.66 g/cc. The frequency distribution of a Crystal Ball sample of 5,000 values is shown in Figure 6. This is rather conservative in the sense that other choices, such as a uniform distribution, would result in higher estimates of the number of drums that would violate the Tc-99 Class A limit.

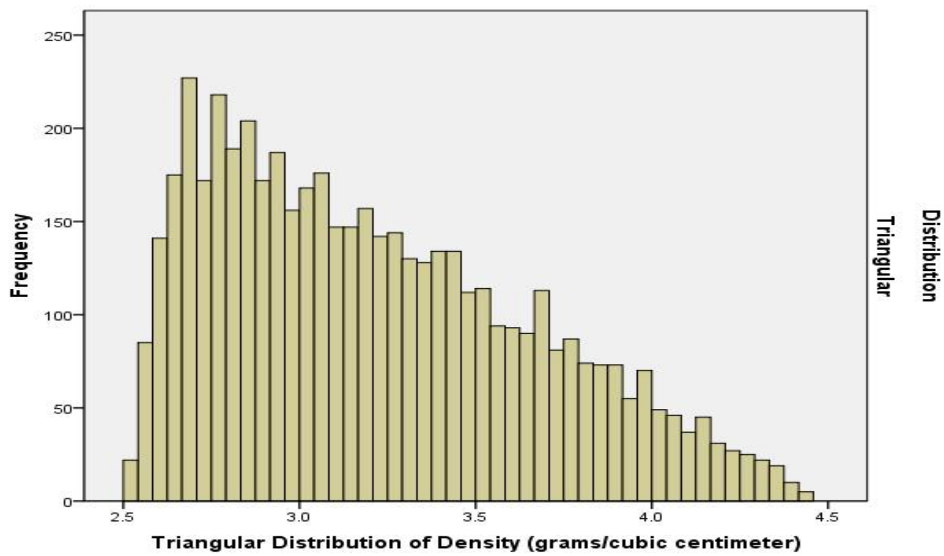

Figure 6: Triangular Distribution Selected for Simulation of Waste Density

2. Simulation Results

The DOE (in Parkinson's memo) reports sampling only 33 drums of about 33,000 drums of depleted uranium oxide. The memo declares that "all samples" meet the Waste Acceptance Criteria (WAC), but this assurance is provided using a single, low point estimate for density of 2.66 grams/cc, without taking into account stated variation in density of 2.5 to 4.5 grams/cc. It is also misleading in that the uncertainty in the Tc-99 content is ignored. The DOE did not report the uncertainty accompanying these calculations. As a result, the DOE memo gives a misleading impression that the 33,000 drums are in compliance with the Tc-99 Class A low-level waste limit of 0.3 Ci/m^3.

This paper addresses the issue of uncertainty in the technetium-99 calculations through the use of Monte Carlo simulation models. The waste activity and waste density probability distributions derived in the previous section were applied in Crystal Ball. One model was constructed for each of the four probability distributions selected as a model of the specific activity. Each model simulates the activity in 33,000 drums containing waste with random specific activity from the appropriate distribution multiplied by a random density selected from the triangular distribution described above. Results of the simulation are shown in Figure 7 for each of the four selected probability distributions. The vertical line in the figure shows the Envirocare (now known as EnergySolutions) Waste Acceptance Criterion limit for technetium-99, which is the same as Utah's Class A limit for this radionuclide. For each type of distribution, the upper tail of the distribution of drum activities extends beyond Utah's Class A limit for technetium-99.

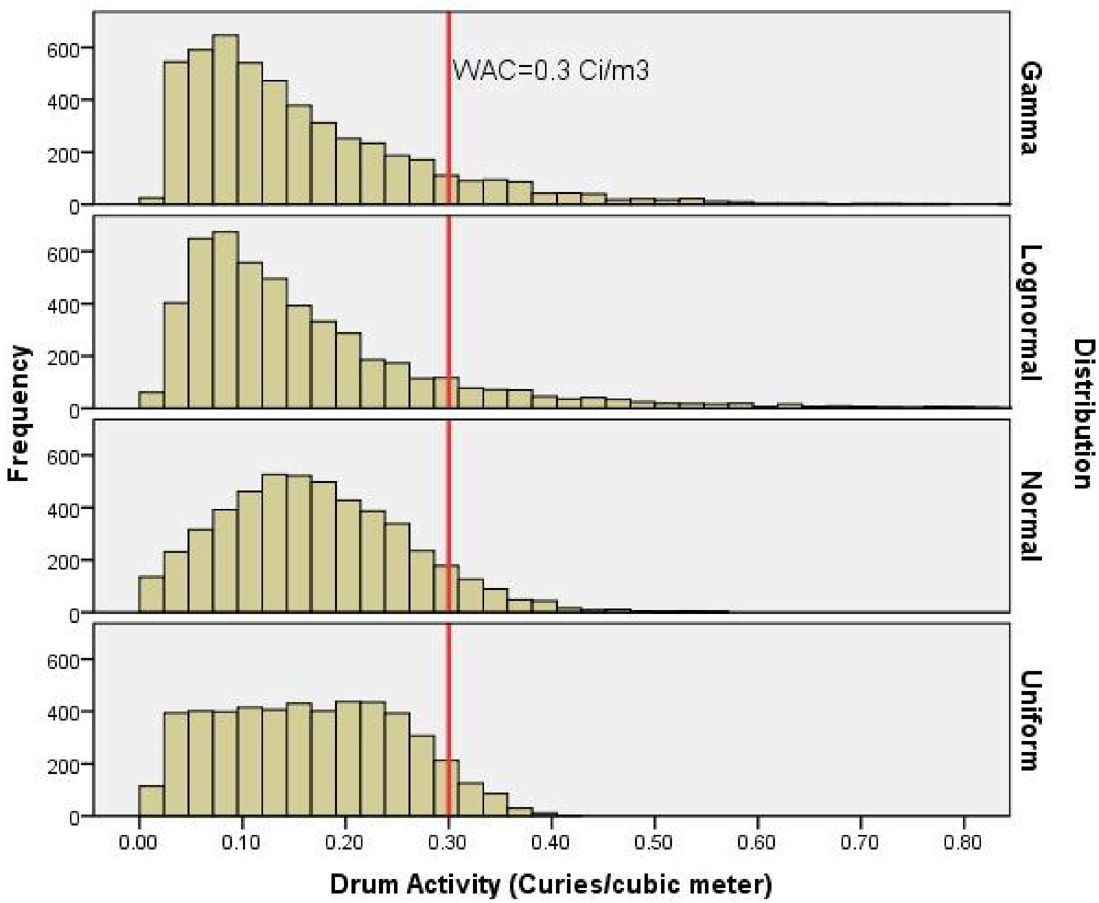

Figure 7: Four Simulated Distributions of Drum Activity Compared with Waste Acceptance Criterion (WAC)—i.e., the Class A limit—for Technetium-99

Each simulation results in an estimate of the count of the number of containers with activity exceeding the WAC of 0.3 Ci/m^3. This count was recorded by Crystal Ball after each iteration of the model. The simulation of the 33,000 drums was repeated 5,000 times to determine uncertainty in the number of containers over the WAC. The results of the simulation are shown in Figure 8. The uncertainty in the number of drums exceeding the WAC is relatively small when compared with the much larger variability due to the type of probability distribution selected for the specific activity. A substantial number of drums exceed the WAC, independent of the choice of the distribution of Tc-99 concentrations. Hence, this is a robust result, given the measurements and data in the Profile Record.

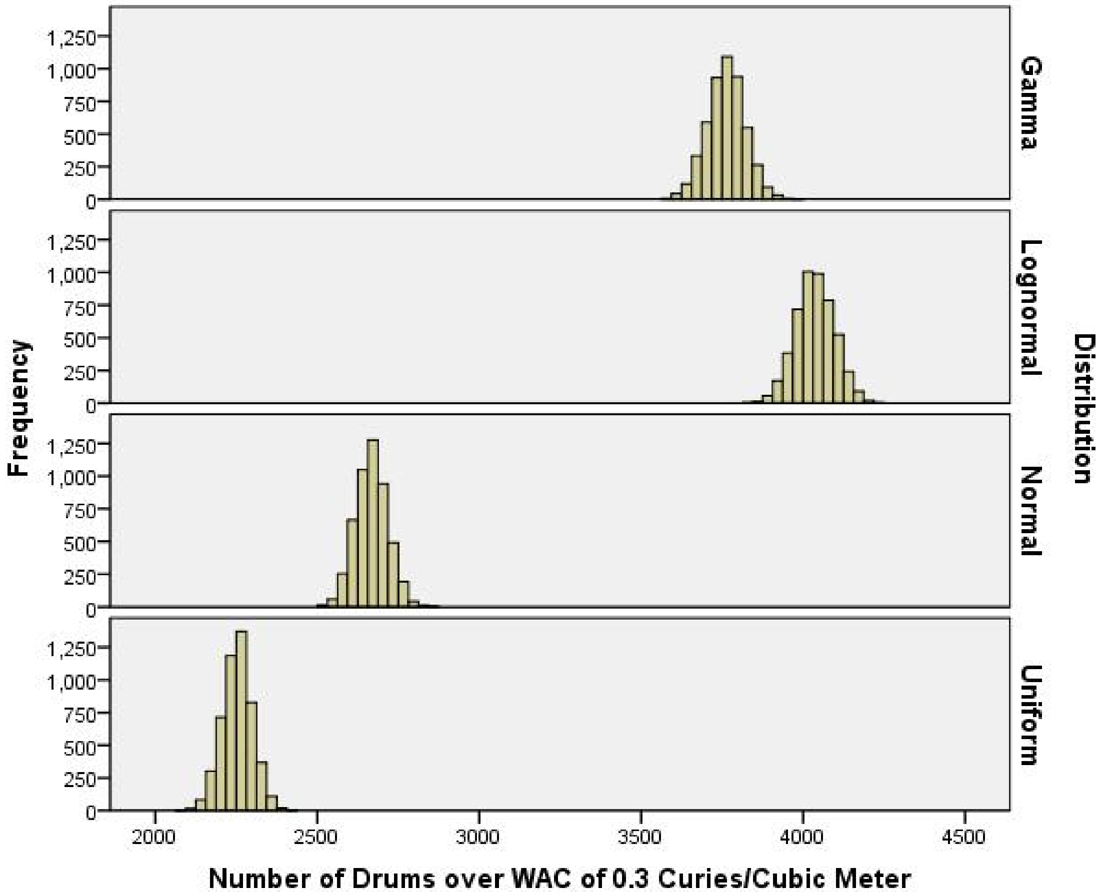

Figure 8: Simulated Number of Drums Exceeding Waste Acceptance Criterion (WAC) for Technetium-99

Table 6 shows the best point estimate, the arithmetic mean of the 5,000 iterations, for the number of drums exceeding the WAC for technetium-99. The best estimates range from over 2,000 drums to 4,000 drums. The simulated 95% and 99% confidence intervals for the number of drums exceeding the WAC under each selected distribution are also shown in the table. Numerical values for the upper and lower bounds of the 95% and 99% confidence intervals for the number of drums over the WAC are shown in Table 7. The uncertainty ranges for each best estimate are only a small fraction of the estimate, ranging up to approximately ±6%.

Table 7 also contains a consensus estimate for the number of drums exceeding the WAC in the final row of the table. The consensus estimate was obtained as the simple arithmetic average of the four best estimates. The confidence intervals for the consensus estimate of the number of drums exceeding the WAC are derived using the t-distribution with three degrees of freedom. The 99% confidence interval for the consensus estimate ranges from approximately 700 to 5,700 drums. Based on the available data and the assumptions of the simulation, it is almost a certainty that hundreds, perhaps thousands, of the 33,000 drums will exceed Utah's Class A limit for technetium-99.

Table 6: Best Estimates for the Number of Drums Exceeding the Waste Acceptance Criterion (Class A limit) for Technetium-99, with 95% and 99% Confidence Intervals

Assumed Distribution	Best Estimate	95% Confidence Interval	99% Confidence Interval
Uniform	2,253	± 92	± 122
Normal	2,667	± 97	± 129
Gamma	3,763	± 114	± 151
Lognormal	4,036	± 118	± 154

Table 7: Range of Estimates for the Number of Drums Exceeding the Waste Acceptance Criterion (Class A limit) for Technetium-99

Assumed	Best	95% Confidence Interval		99% Confidence Interval	
Distribution	Estimate	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Uniform	2,253	2,162	2,345	2,131	2,371
Normal	2,667	2,572	2,764	2,544	2,796
Gamma	3,763	3,650	3,877	3,614	3,914
Lognormal	4,036	3,922	4,154	3,882	4,186
Consensus Estimate[18]	3,180	1,819	4,541	682	5,678

[18] The consensus estimate is the arithmetic mean of the best estimates obtained from the four simulations of technetium-99 activity. Confidence intervals for the consensus estimate of the number of drums exceeding the WAC are derived using the t-distribution with three degrees of freedom.