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Revised Cost Savings Estimate with Uncertainty for Enhanced Sludge Washing of Underground Storage Tank Waste

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ABSTRACT

Enhanced Sludge Washing (ESW) has been selected to reduce the amount of sludge-based underground storage tank (UST) high-level waste at the Hanford site. During the past several years, studies have been conducted to determine the cost savings derived from the implementation of ESW. The tank waste inventory and ESW performance continues to be revised as characterization and development efforts advance. This study provides a new cost savings estimate based upon the most recent inventory and ESW performance revisions, and includes an estimate of the associated cost uncertainty. Whereas the author's previous cost savings estimates for ESW were compared against no sludge washing, this study assumes the baseline to be simple water washing which more accurately reflects the retrieval activity alone. The revised ESW cost savings estimate for all UST waste at Hanford is \$6.1 B $\pm$ \$1.3 B within 95% confidence. This is based upon capital and operating cost savings, but does not include development costs. The development costs are assumed negligible since they should be at least an order of magnitude less than the savings. The overall cost savings uncertainty was derived from process performance uncertainties and baseline remediation cost uncertainties, as determined by the author's engineering judgement.

INTRODUCTION

There exists approximately 100 million gallons of liquid-based radioactive waste in underground storage tanks (USTs) at Department of Energy (DOE) sites across the United States. Approximately 65 million gallons are stored at the Hanford site. The DOE is responsible for permanent immobilization and disposal of this tank waste. The vast majority of UST waste at Hanford can not be classified as low-level waste (LLW). LLW can generally be disposed of subsurface on-site; whereas, high-level waste (HLW) must be disposed in an underground repository such as that planned for Yucca Mountain. Since LLW disposal is obviously much less expensive than HLW disposal, the plan for remediation at Hanford is to separate the UST waste into a small volume of HLW and large volume of LLW.

Of the 65 million gallons of UST waste at Hanford, approximately 20 vol% is solids-based consisting of sludge and slurry solids, and the remaining 80 vol% is liquid-based consisting of supernate, salt cake, and slurry liquid (see Figure 1). These solids consist of well over 99 wt% non-radionuclides. Without solids-based processing, the non-radionuclides will dictate a very large volume of immobilized HLW for the underground repository. Therefore, partial separation of some non-radionuclides (such as aluminum, chromium, sodium, and phosphorus) from the solids, is an essential step in reducing the final amount of HLW disposed of in the underground repository. The aluminum, chromium, sodium, and phosphorus separated from solids-based waste can then be disposed of as LLW.

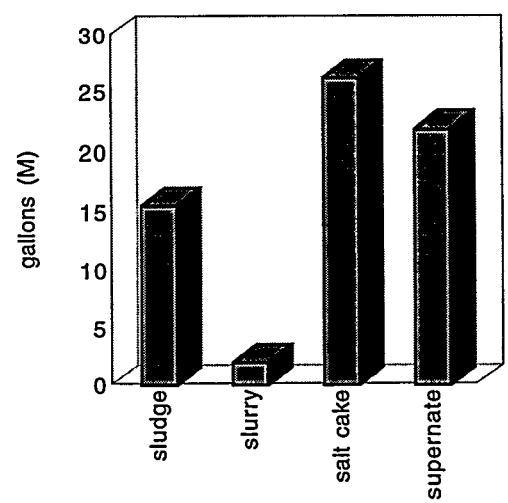

Figure 1. UST waste types at Hanford

Approximately 15 million gallons of the UST waste at Hanford is solids-based, and amenable to volume reduction by a process referred to as sludge washing. Due to the relative high non-radionuclide density, the solids-based waste has a much greater affect on the final amount of immobilized HLW

sent to the underground repository, than that resulting from liquid-based waste. In fact, even with ESW the solids-based waste dictates approximately 85 vol% of the final immobilized HLW for the repository. Even with ESW, radionuclide loading in the immobilized HLW, due to the solids-based waste is about fifty-times less than that permitted by radionuclide heat generation alone [1]. Consequently, chemical processing which significantly reduces the solids-based waste non-radionuclide concentration can have a very large impact on the overall remediation cost. The relative high non-radionuclide concentration of the solids-based waste prior to sludge washing is shown by Figure 2.

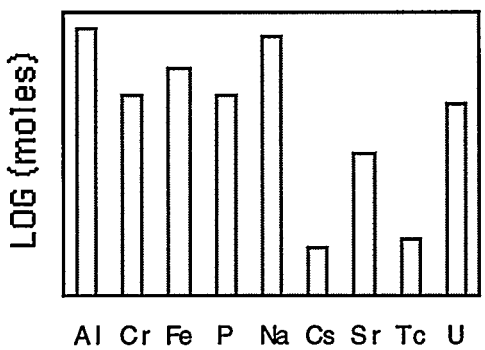

Figure 2. Hanford pre-washed solids composition

Sludge washing development has been funded by the Department of Energy's Office of Science and Technology. Since each of the 177 USTs at Hanford has a unique waste composition, no single set of sludge wash process conditions will minimize the final immobilized HLW. The sludge wash process being developed at Hanford is referred to as Enhanced Sludge Washing (ESW), indicating development beyond a generic process for all waste. Process parameters being optimized include time, temperature, caustic (NaOH), additives targeting dissolution of specific species such as chromium, and flocculents for settling. The time affects operating cost, the temperature affects capital cost, and the caustic concentration affects the amount of LLW if caustic recycle (currently not the baseline) is not used and affects the degree of radionuclide dissolution. Excessive radionuclide dissolution can increase the processing complexity of the liquid-based waste. As an example, past studies have indicated only cesium need be removed from the liquid-based waste; however, excessive strontium dissolution during ESW may force its separation from the liquid-based waste as well.

Two past ESW cost studies have been conducted by the author. The first study [2] was based upon the original Westinghouse Tank Waste Remediation System (TWRS) flowsheet, which included the ESW separation factors of 1995 [3]. The second study [4] was a revised version of the first, based upon the initial Westinghouse Privatization flowsheet, which included the ESW separation factors of 1996 [5]. The first study determined the potential ESW versus no-wash cost savings to be $8.7 B, and the second study determined the potential ESW versus no-wash cost savings to be $6.3 B.

This effort is then the latest revision in the author's series of ESW cost studies, and is based upon revised waste inventories [6] and ESW separation factors of 1997 [7]. In addition, (1) this study uses a different baseline against which the ESW is compared, and which represents actual retrieval operations more accurately, and (2) includes an estimate of the cost savings uncertainty based upon statistical analyses.

SUMMARY

Based upon the TWRS revised inventory and latest ESW separation factors, the potential cost savings derived from the implementation of ESW at Hanford is $6.1 B ± $1.3 B within 95% confidence (see Figure 3). This savings represents the use of ESW rather than simple water washing, and neglects the cost due to development based upon the savings being at least an order of magnitude greater than the development cost. The overall cost savings uncertainty is derived from uncertainties in the (1) ESW separation factors, (2) baseline TWRS remediation cost, and (3) capital cost scaling factors. The overall cost savings uncertainty was estimated from the individual uncertainties by the use of a method similar to a classical Analysis of Variance (ANOVA). The uncertainty difference between the simple water wash and ESW

was determined by the use of a pooled-variance.

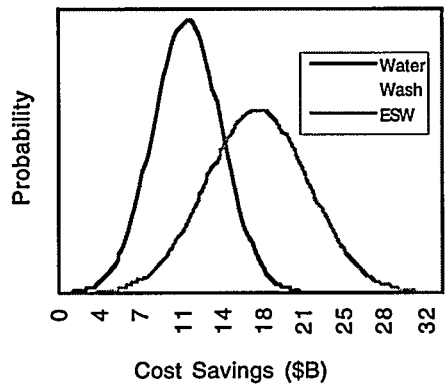

Figure 3. Cost savings distributions

Defining the baseline cost against which ESW should be compared was not straight-forward. It can be argued that some degree of ESW is possible without any development. However, as an example, the process parameters such as settling time and radionuclide dissolution would need to be evaluated for each waste type regardless of the exact ESW conditions. Inadequate settling may demand excessive filtration. Excessive dissolution of the solids may require the addition of a strontium separation step in the treatment of the liquid-based waste. Consequently, a simple water wash was selected as the basis for the baseline remediation cost.

The statistical analyses developed for this effort is based upon a closed analytical solution for use with a spreadsheet, rather than more involved Monte Carlo techniques. This was purposely done to keep the methodolgy transportable for evaluation and use by the interested technical community. The closed solution is achieved by limiting the degrees of freedom, defined by the number of uncertain process parameters. The methodology can be extended to many uncertain process parameters by the use of a computer solution more elaborate than that possible with a simple spreadsheet. However, with careful judgement, the use of only the most significant uncertain process parameters can yield an accurate determination of the overall cost uncertainty.

Quantitative definition of the individual process parameter uncertainty is probably the subject of greatest debate for this study. The author has used his engineering judgement for defining these uncertainties in terms of triangular or trapezoidal distributions. These distributions would be best defined in the future by the combined interested technical community.

ANALYSES

The ESW cost savings was determined in a manner identical to previous cost studies completed by the author. [2&4] In particular, the analysis of Reference 4 was revised by (1) an updated waste inventory [6], and (2) updated ESW separation factors [Table 4.4-1 of Reference 7]. Reference 6 provided only the total tank waste, not the solid versus liquid fraction; therefore, the solid fraction of each species was determined from Table 13 of Reference 5. This analysis also departed from the previous by changing the base case against which the ESW costs were compared. The author's previous analyses compared ESW costs against no sludge washing. This analysis has compared ESW costs against sludge washing with only water, as defined by Reference 5, page 85. Reference 5 defines simple water washing to dissolve 75% of that dissolved by ESW.

Based upon the process parameters specified above, the cost savings using ESW rather than the simple water wash is $6.1B, when determined in a fashion identical to Reference 4.

The ESW cost uncertainty was estimated in a fashion similar to that done by the author for ion exchange resin [8], described as follows.

(1) Potential process and cost parameters were selected, and their uncertainties estimated by engineering judgement, which were thought to have a significant affect on the remediation cost.

(2) The three process parameters which had the most significant affect on the remediation cost were selected by way of a sensitivity analysis. The sensitivity analysis was accomplished by

propagating the process and cost parameter uncertainties to the overall remediation cost by way of an integrated process/cost model.

(3) All possible cost savings outcomes of equal probability, where combined for determination of the mean and variance, as done for a classical Analysis of Variance (ANOVA).

(4) The results of the ANOVA were applied to a normal distribution, and a pooled-variance was used to determine the final cost savings uncertainty with its associated confidence interval.

Figures 4, 5 and 6 show the three most significant process and cost parameters, and their estimated distributions. The author judged that ESW separation factors of 90% and 105% of the expected values (Table 4.4-1 of Reference 7), would have half the probability of occurrence (see Figure 4). This factor was corrected for only chromium dissolution since it alone dictated the final amount of immobilized HLW glass.

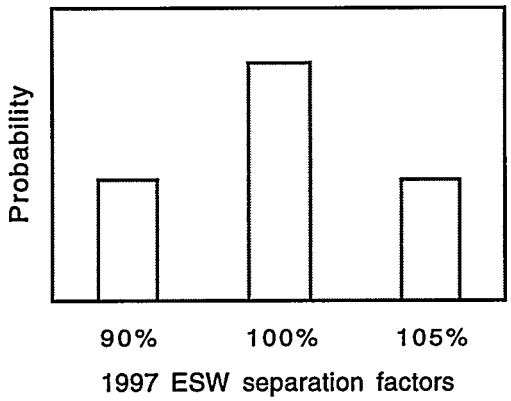

Figure 4. ESW separation factor uncertainty

The author judged that a UST remediation cost of 120% of the expected value (Table F-36 of Reference 10), would have one-third the probability of occurrence as the expected value(see Figure 5). The expected value was based upon the most comprehensive cost analysis available, completed for the TWRS Environmental Impact Statement in 1995. While many people involved with TWRS remediation expect the costs to exceed more than 120% of the 1995 estimate, a consensus does not yet exist.

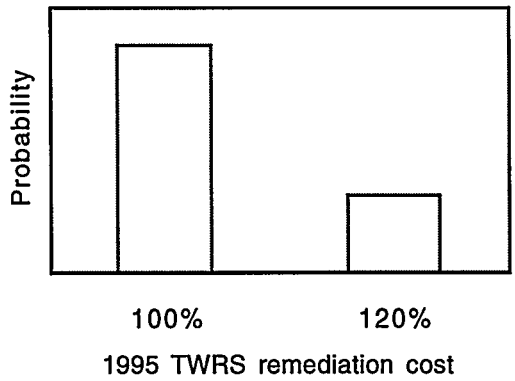

Figure 5. Remediation cost uncertainty

The author judged that a capital cost scaling factor of 0.4, would have one-third the probability of occurrence as the expected value of 0.7 (Table 9-3, Reference 11), see Figure 6. The expected value was based on that for a typical chemical processing plant. The reduced factor of 0.4 represents a conservative estimate, possibly for nuclear materials processing.

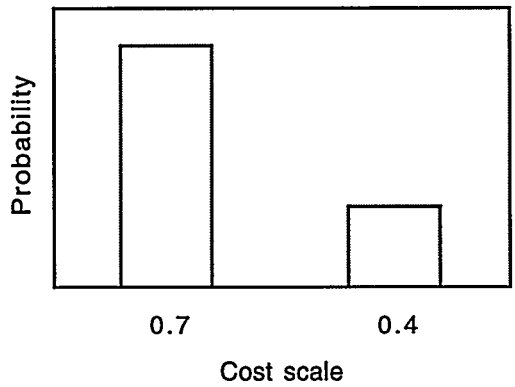

Figure 6. Capital cost scaling uncertainty

The ESW cost savings for each of the process or cost parameter occurrences shown in Figures 4, 5 and 6, are shown in Table 1. Similar costs were determined for simple water washing and are shown in Table 2.

A matrix of each possible outcome of equal probability can then be prepared as shown by Table 3.

Table 1. ESW cost savings outcomes ($B)

		Remediation Cost	
		100% TWRS 1995	120% TWRS 1995
Cost Scale 0.4	90% ESW	8.31	9.97
	100% ESW	9.61	11.54
	105% ESW	10.16	12.20
Cost Scale 0.7	90% ESW	15.75	18.90
	100% ESW	17.87	21.44
	105% ESW	18.71	22.45

Table 2. Simple water washing cost savings outcomes ($B)

		Remediation Cost	
		100% TWRS 1995	120% TWRS 1995
Cost Scale 0.4	90% wash	5.28	6.33
	100% wash	5.93	7.11
	105% wash	6.27	7.52
Cost Scale 0.7	90% wash	10.35	12.42
	100% wash	11.56	13.87
	105% wash	12.18	14.61

Table 3. Outcomes of equal probability

Cost Scale	Wash	Cost		Cost Scale	Wash	Cost
0.7	90%	100%		0.7	90%	100%
0.7	90%	100%		0.7	90%	100%
0.7	90%	100%		0.7	90%	100%
0.7	90%	100%		0.7	90%	100%
0.7	100%	100%		0.7	100%	100%
0.7	100%	100%		0.7	100%	100%
0.7	100%	100%		0.7	100%	100%
0.7	100%	100%		0.7	100%	100%
0.7	100%	100%		0.7	100%	100%
0.7	100%	100%		0.7	100%	100%
0.7	100%	100%		0.7	100%	100%
0.7	100%	100%		0.7	100%	100%
0.7	105%	100%		0.7	105%	100%
0.7	105%	100%		0.7	105%	100%
0.7	105%	100%		0.7	105%	100%
0.7	105%	100%		0.7	105%	100%
Cost Scale	Wash	Cost		Cost Scale	Wash	Cost
0.7	90%	100%		0.4	90%	120%
0.7	90%	100%		0.4	90%	120%
0.7	90%	100%		0.4	90%	120%
0.7	90%	100%		0.4	90%	120%
0.7	100%	100%		0.4	100%	120%
0.7	100%	100%		0.4	100%	120%
0.7	100%	100%		0.4	100%	120%
0.7	100%	100%		0.4	100%	120%
0.7	100%	100%		0.4	100%	120%
0.7	100%	100%		0.4	100%	120%
0.7	100%	100%		0.4	100%	120%
0.7	100%	100%		0.4	100%	120%
0.7	105%	100%		0.4	105%	120%
0.7	105%	100%		0.4	105%	120%
0.7	105%	100%		0.4	105%	120%
0.7	105%	100%		0.4	105%	120%

Figures 7 and 8 show the actual distribution of cost savings for ESW and simple water washing respectively, as determined from the outcomes of equal probability shown in Table 3, derived from Tables 1 and 2. In order to determine the ESW and simple water washing cost difference uncertainty, both distributions of Figures 7 and 8 were approximated as normal.

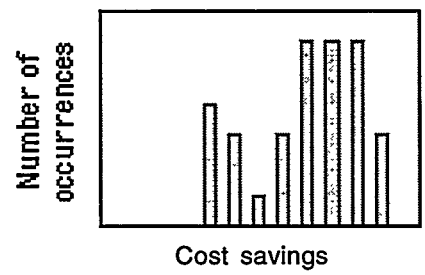

Figure 7. Cost savings distribution for ESW

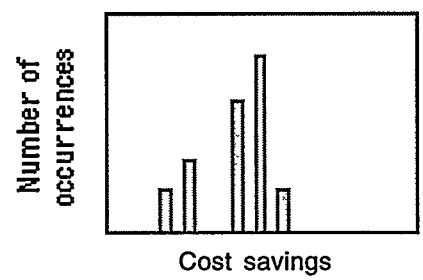

Figure 8. Cost savings distribution for simple water washing

Figure 7 and 8 are converted to normal distributions by determining the mean with Equation 1, the variance with Equation 2, and the overall continuous distribution with Equation 3. The subscripts i, j, and k represent the individual effects, i.e. wash separation factor, remediation cost, and cost scaling. The parameter "C" represents the cost savings, and "m" represents the number of outcomes of equal probability, i.e. four.

$$\overline{C} = \frac{1}{m^3}\sum_{i=1}^{m}\sum_{j=1}^{m}\sum_{k=1}^{m} C_{i,j,k} \qquad \text{Eq. 1}$$

$$\sigma^2 = \frac{1}{(m^3-1)}\sum_{i=1}^{m}\sum_{j=1}^{m}\sum_{k=1}^{m}\left(\overline{C} - C_{i,j,k}\right)^2 \qquad \text{Eq. 2}$$

$P(C_i)$ shown in Equation 3 is the probability of cost savings C_i.

$$P(C_i) = \frac{e^{-\left[\frac{1}{2}\left(\frac{C_i - \bar{C}}{\sigma}\right)\right]^2}}{\sqrt{2\Pi}\sigma} \qquad \text{Eq. 3}$$

Figures 9 and 10 display the approximated normal distribution for ESW and simple water washing cost savings respectively.

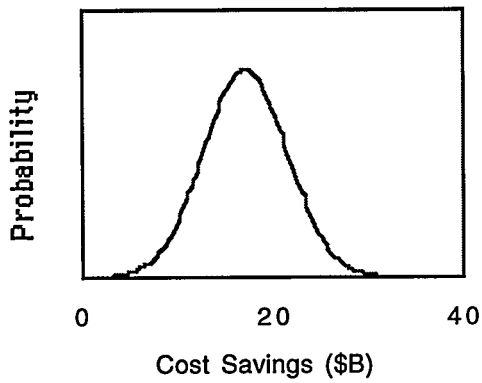

Figure 9. Normal distribution for ESW cost savings uncertainty

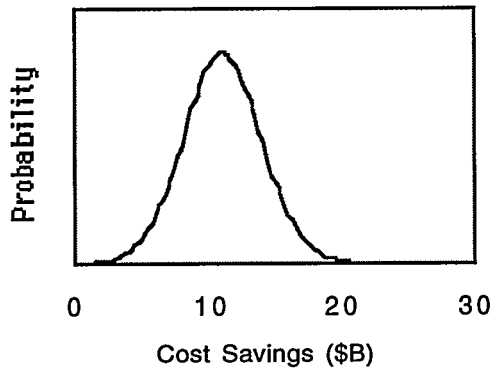

Figure 10. Normal distribution for simple water washing cost savings uncertainty

The uncertainty in cost savings between ESW and simple water washing is then estimated by the pooled variance as determined by Equation 4, and the 95% confidence interval determined by the Student's-t estimate represented by Equation 5.[Section 2.3.2 of Ref. 12] The subscripts "a" and "b" represent ESW and simple water washing.

The pooled-variance (m=4 & n=3) is:

$$\sigma_p^2 = \frac{(m_a^n - 1)\sigma_a^2 + (m_b^n - 1)\sigma_b^2}{m_a^n + m_b^n - 2} \qquad \text{Eq. 4}$$

The approximate uncertainty at the 95% confidence interval (m=4 & n=3) is:

$$2\sigma_p \sqrt{\frac{1}{m_a^n} + \frac{1}{m_b^n}} \qquad \text{Eq. 5}$$

Applying Equations 1 and 2 to Table 3 for both the ESW and simple water wash, where the cost savings value related to each occurrence of Table 3 was derived from Tables 1 and 2, yields the following means and variances.

ESW:

$$\bar{C} = \$17.1\text{ B}$$

$$\sigma^2 = (\$4.4\text{ B})^2$$

Simple Water Wash:

$$\bar{C} = \$11.0\text{ B}$$

$$\sigma^2 = (\$2.9\text{ B})^2$$

And finally, the actual ESW cost savings is the difference between ESW and the simple water wash.

$17.1 B - $11.0 B = $6.1 B

And the associated uncertainty as determined by the pooled variance, and Student's-t distribution, is determined as follows.

$$\sigma_p^2 = \frac{(4^3 - 1)\ 4.4^2 + (4^3 - 1)\ 2.9^2}{4^3 + 4^3 - 2} = 13.9$$

$$2\sigma_p \sqrt{\frac{1}{m_a^n} + \frac{1}{m_b^n}} = 2\sqrt{13.9}\sqrt{\frac{1}{4^3} + \frac{1}{4^3}} = 1.3$$

The overall cost savings uncertainty is $1.3 B at the approximate 95% confidence interval.

RECOMMENDATIONS

The author has two primary recommendations for further improving the accuracy of the (1) ESW cost savings estimate, and (2) associated uncertainty estimate.

First, it is recommended that the baseline against which ESW is compared should be re-evaluated and commonly selected by the interested technical community. For this study the baseline was assumed to be simple water washing.

Second, the uncertainty distributions for the most significant effects should also be re-evaluated and commonly selected by the interested technical community. For this study the most significant effects were found to be the separation factors, the remediation cost, and the cost scaling factors.

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