Development of an Alternative Release Limit for a Former Uranium and Thorium Processing Plant in Cushing Oklahoma

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ABSTRACT

The purpose of this presentation will be to describe how, through dose modeling and analysis, a complex site was able to obtain an Alternative Release Limit (ARL) that adequately protected the environment, met regulatory approval, and saved money in the process.

The Kerr-McGee Refinery Site in Cushing, OK supported an experimental facility that processed nuclear fuel materials from 1963 to 1966. Radiological contaminants at the site as a result of operations consist of natural thorium and isotopes of uranium (Th-228, Th-232, U-234, U-235 and U-238).

Site contamination existed in both surface and sub-surface soils and within a shallow aquifer. After the soil was remediated to acceptable regulatory limits, however, the potential existed for residual groundwater contamination to result in exposure to individuals following site closure. Traditional exposure pathway analysis for the resident farmer seemed to indicate that this exposure was excessive.

A closer look at the exposure pathways present in this rural location showed that groundwater contamination existed in a shallow aquifer insufficient to support significant irrigation activities and was of sufficiently poor water quality that it could not be used for drinking water.

Through the determination of aquifer yield pumping tests, agreement from the Oklahoma Department of Environmental Quality, and sensitivity and uncertainty analysis using Monte Carlo techniques, it was shown that the average member of the critical population was adequately protected in the current site configuration without further remediation.

This paper describes the analytical methods and models used to apply the general dose limit of 0.25 mSv yr^{-1} (25 mrem yr^{-1}) to the particulars of the Cushing Site, and demonstrates how these methods achieved a much higher ARL for total uranium in groundwater that was accepted by the regulators and achieved significant savings for the Licensee.

INTRODUCTION

This paper summarizes the methodology of NUREG/CR-5512 [1] and, to a lesser extent, RESRAD [2], for determining the potential dose to a resident farmer scenario due to uranium contamination in groundwater. The calculations are based upon an initial concentration of 0.037 Bq L^{-1} (1 pCi L^{-1}) of uranium in the groundwater. The contamination is carried through the various potential pathways to humans, and the resulting dose per unit concentration (in mSv yr^{-1} Bq^{-1} L (mrem yr^{-1} pCi^{-1} L)). The Alternate Release Limit (ARL) for uranium in groundwater is then derived based upon the regulatory limit of 0.25 mSv yr^{-1} (25 mrem yr^{-1}) to the average member of the critical population. In this case, the exposure pathway scenario assumes that the resident farmer is the average member of the critical population. It is important to emphasize that for this analysis, the only contamination that is assumed to exist in any pathway is as a result of the contaminated groundwater used for irrigation. Specifically, the soil is assumed to not be contaminated initially but reaches a contaminant concentration in the soil (root zone) as a result of the use of contaminated irrigation water.

The resident farmer scenario assumes that an individual spends a majority of time on his/her parcel of land. The individual builds a house, drills a well, and raises crops in order to support the resident farmer lifestyle. Due to the limitations of the quantity and variety of fruits and vegetables produced, only 50% of the total produce consumed is assumed to be grown on the farmer's land. Due to the use of the groundwater well, the individual is exposed to a number of pathways. Namely:

- Ingestion of soil
- External exposure to radiation from contaminated soil while outdoors
- Inhalation exposure of resuspended soil while indoors and outdoors
- Ingestion of fruits and vegetables

The drinking water, animal pathway and fish ingestion pathways are specifically excluded from the analysis. This abbreviated paper first presents the exceptions to the default pathway parameters, then concludes by summarizing the ARL. This paper first presents the exceptions to the default pathway parameters, then reviews the calculational methodology and concludes by summarizing the ARL.

METHODS

A sensitivity and uncertainty analysis was performed, relying primarily on the input of NUREG 6697 [3] for the distribution of many of the parameters. Some parameters were modified by taking into consideration local climate or available data. In several instances, parameters were modified from those recommended in NUREG 6697 due to the intent of the model. For the analysis described in this paper, it is the top soil layer (root zone) that is of primary interest, some modifications were made to infiltration parameters to ensure that a realistically conservative approach was used in the calculation of the resulting leach rate from the root zone. The following bullets describe key assumptions or parameters and criteria used for this modeling that differ from generally recommended default values:

- **Drinking Water Ingestion –** The shallow groundwater for the Cushing Site is described as yielding low quantities of poor quality water with no known drinking water wells screened in the Vanoss Group within a mile radius of the site[a]. Both on the Cushing site and in the surrounding vicinity, the productive aquifer used is the Vamoosa-Ada Aquifer. The Vamoosa-Ada on site well is at a depth of approximately 155 meters. The City of Cushing has several municipal water-supply wells in the Vamoosa-Ada Aquifer ranging in depths from 120 meters to as deep as 210 meters [4]. The shallow Vanoss Group is hydraulically separated from the deeper Vamoosa-Ada Aquifer.

  The State of Oklahoma Department of Environmental Quality (DEQ) stated the following: "Shallow groundwater generally occurs in the Vanoss Group 3 to 4.6 meters below the site ground surface. This unit yields low quantities of poor quality water. It is highly unlikely that future residential/commercial drinking water will be established from the shallow groundwater at this site. No known drinking water wells are screened in the Vanoss within a one-mile radius of the site"[a] .

  Given that the Vamoosa-Ada Aquifer is available onsite and in the vicinity of the Cushing site, no drinking water intake is assumed from the Vanoss Group. It is highly unlikely that the Vanoss Group would support the adapted lifestyle scenario of a resident farmer. The modeling results presented in this technical paper should therefore be considered highly conservative.
- **Animal Pathway** – Aquifer yield tests were performed to quantify the supply of groundwater available from the Upper Vanoss Aquifer. That yield test determined that sufficient waste volume only exists to supply a 30 m x 30 m farm assuming a trickle irrigation method at 2.5 cm week^{-1} of

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[a] Shults, D. Letter to J. Lux, Kerr_McGee Corp. from Darrell Shults, Senior Hydrologist, Department of Environmental Quality, State of Oklahoma. September 19, 1997.

irrigation [5]. Insufficient volume exists to support the inclusion of farm animals in the model as well. The animal pathway is therefore removed as a possible pathway in favor of the more dominant plant ingestion pathway.

- **Overhead Spray Irrigation versus Trickle Irrigation** – The Upper Vanoss Yield test report by Thomas also calculated water requirements for the assumed family farm. Based upon the limited water volume and input from a Payne County horticulturalist [5], trickle irrigation was viewed as the only viable means of irrigating the plot size given the available groundwater pumping rate. This selection of trickle irrigation over overhead irrigation is directly related to the increased evapotranspiration and resultant increased water requirements for overhead irrigation. However, this model will remain conservative and assume that an overhead irrigation system is used due to the increased availability of contamination to plants from direct deposition.
- **ICRP 72 Ingestion and Inhalation Dose Coefficients** – The ingestion and inhalation dose conversion factors (DCFs) from ICRP 56+ documents are summarized in ICRP 72 [6] and applied in this analysis. The ICRP 72 DCFs were developed specifically for calculation of dose to members of the public. ICRP 72 retains the gastrointestinal tract model used in ICRP 30, but uses the updated tissue weighting factors presented in ICRP 60, and revised biokinetic information to reflect increased knowledge in the uptake and retention of various elements in the body. ICRP 72 inhalation factors represent the application of an updated lung uptake and retention model.
- **Soil Classification -** The results of three soil samples collected at the site result in a USCS classification of lean clay with sand. Lean clays contain less of the clay minerals that absorb more water and contain a correspondingly smaller amount of ion exchange sites than does a "fat" clay with a higher mineral content. The lean clay with sand USCS classification corresponds to a silty clay classification using the USDA classified soil textures used in NUREG 6697. The silty clay soil affects the distributions of the soil density, total porosity, distribution coefficient for uranium, the hydraulic conductivity, and the soil type b parameter. The distributions used for all of these parameters is the default for silty clay soils recommended by NUREG 6697.
- **Distribution Coefficients –**The recommended values for the distribution coefficient cannot differentiate between the various subtypes of clay soils. The uranium mean Kd of 1,600 $cm^3\ g^{-1}$ for clay is used and the upper bound is limited to 100,000 $cm^3\ g^{-1}$.
- **Translocation factor for non leafy vegetables** – A value of 0.055 is used since a varied crop type would be utilized and the results would tend toward the mean value as opposed to an upper bound value.
- **Losses during food preparation** – The removal of contamination is only considered for the resuspended soil fraction and not the contamination initially deposited from irrigation or via root uptake. A removal fraction of 50% is assumed for this particular aspect of soil residue from resuspended material. This assumption is viewed as conservative as it does not consider the added losses due to peeling, cooking or other processes that would result in additional reductions in plant concentrations [7].

In addition to the parameters discussed above, a number of parameters required specific consideration as the endpoint of this analysis is the root zone and not the infiltration of contamination to the groundwater as is common is most scenarios. The following parameters are discussed in this context:

- Irrigation rate – two factors at play. First, a smaller irrigation rate results in a lesser amount of leaching from the root zone. Second, a smaller irrigation rate results in less contamination applied to the root zone. The second factor dominates such that a smaller irrigation rate would not be conservative as it would allow for a significantly higher release limit. The conservative value of 2.5 cm $week^{-1}$ is recommended by a Payne County horticulturalist and is used in this instance.
- Evapotranspiration coefficient (ET) – Modification of this parameter has little impact on the allowable release limit. NUREG/CR-6697 recognizes that small area farmers would tend to over irrigate thereby biasing the ET lower.

- Runoff coefficient – The sensitivity analysis shows that this parameter has little impact on the calculated release level. This minor impact is due to the fact that the soil concentration used in the calculations is the result of 50 years of continuous irrigation and rainfall. The recommended distribution from NUREG 6697 is therefore used.
- Root depth – The recommended values from the USDA National Resources Conservation Service National Engineering Handbook part 652, Irrigation Guide (NRCS) are used in place of NUREG 6697 guidance for several reasons. First, NUREG 6697 guidance is for entire United States and the range is biased on the high side to arid climates so the distribution is not appropriate. Second, according to Chris Stoner (OK NRCS), the plow pan plays a major role in limiting root depth in OK. Breakup of the plow pan occurs periodically at 38 cm to 46 cm breakup depth. The plow pan depth is typically 20 to 30 cm. The root depth distributions used are conservative without including the increased root depths of arid climates.

The calculations for this analysis were conducted in Excel® spreadsheets for ease of application and review. In addition, by performing all calculations within the spreadsheets this allowed for a straightforward application of the program Crystal Ball [8].

Inadvertent Soil Ingestion

Ingestion of contaminated soil is possible as a result of transfer to vegetables, fruits, and hands [1]. Although the amount ingested depends upon the activities performed and personal habits, a default value of 18.25 g/y is assumed [9, 3]. The equation for calculating the ingestion dose is as follows [1]:

$$Dose_{soiling} = C_{soil} * IR * ED * DCF * \frac{100{,}000}{27} \qquad \text{(Eq. 1)}$$

Where:

- $Dose_{soiling}$ = Committed effective dose from the ingestion of soil
- C_{soil} = Concentration of soil (Bq/g)
- IR = Ingestion rate of soil (g/day)
- ED = Exposure duration (d/year)
- DCF = Committed effective dose conversion factor for ingestion (Sv/Bq)
- 100,000/27 = Conversion from Sv to mrem and pCi to Bq

External Exposure to Soil

The general formula used for calculating the external effective dose equivalent for outdoor exposure is as follows:

$$ExternalDose = C * DCF * ED * 3600 \qquad \text{(Eq. 2)}$$

Where:

- External dose = Dose in Sieverts (multiply by 100,000 to obtain dose in mrem)
- C = Concentration ($Bq*m^{-3}$)
- DCF = Dose conversion factor, nuclide specific ($Sv*s^{-1}*Bq^{-1}*m^{3}$)
- ED = Exposure duration (hours/year)

- 3600 = Conversion from hours to seconds

The dose conversion factor used in the calculations conservatively assumes an infinite plane source contaminated to an infinite depth [10].

Soil Resuspension and Inhalation

Contaminated soil may also result in exposure due to resuspension and subsequent inhalation. This exposure may occur from soil contaminated through irrigation water.

The resuspension factor does depend upon the activities that are being performed by the resident farmer. The highest dust loading is related to gardening activities, while the lowest is equated to time spent indoors. The equation for calculating the committed effective dose from inhalation is as follows [1]:

$$Dose_{Inhalation} = [(V_x * t_x * CDO * C_{soil} * DCF) + (V_r * t_i * (CDI + P_d * RF_r) * C_{soil} * DCF)] * 10^5 \qquad \text{(Eq. 3)}$$

Where:

- V_x = Breathing rate for time spent outdoors (m^3/h)
- t_x = Time spent outdoors during a year (hours)
- CDO = Dust loading for outdoor activities (g/m^3)
- V_r = Breathing rate for time spent indoors (m^3/h)
- t_i = Time spent indoors during a year (hours)
- CDI = Dust loading for indoor activities (g/m^3)
- P_d = Indoor dust loading on floors (g/m^2)
- RF_r = Indoor resuspension factor (per meter)
- DCF = Inhalation committed effective dose, nuclide and age specific (Sv/Bq)
- 10^5 = Conversion from Sv to mrem

The indoor portion of the above equation differs slightly from the outdoor portion, as it includes contributions from materials blown and soil tracked into the house and resuspended [1].

Ingestion of Fruit and Vegetable Products

The calculation of the concentration on the plant from overhead irrigation involves two separate stages. The first stage determines the amount retained on plants after being sprayed by irrigation water. The second stage calculates the additional contamination as a result of root uptake and resuspension of contaminated soil onto the plant. The two stages are then added to obtain a combined contaminant concentration on edible plant surfaces. The plant concentration is then calculated according to each plant type, and a dose conversion factor is applied to the total intake to calculate the final dose from ingestion of produce.

In order to calculate the concentration on the plant following the initial deposition, an estimate must first be made of the deposition rate [1]:

$$R = \left\{ IR * r_v * T_v * C_w \right\} / Y_v \qquad \text{(Eq. 4)}$$

Where:

- R = Average deposition rate to edible parts of plant from application of irrigation water (pCi/kg*d)
- IR = Application rate of irrigation water (L/m^2*d)
- r_v = Fraction of initial deposition retained on plant (dimensionless)
- T_v = Translocation factor for transfer of radionuclides from plant surfaces to edible parts (dimensionless)
- C_w = Average concentration in irrigation water (assumed constant) (pCi/L)
- Y_v = Plant yield (kg wet weight/m^2)

Following the estimate of the deposition rate, a calculation of the contribution from direct deposition is an ordinary, first order, linear differential equation. The solution to the equation is as follows:

$$C_{plant,deposition} = (R/\lambda)\left\{1 - e^{-\lambda t}\right\} \quad \text{(Eq. 5)}$$

Where:

- $C_{plant,deposition}$ = The radionuclide concentration in the plant from deposition onto plant surfaces (pCi/kg)
- λ = Effective weathering and decay constant (d-1)
- t = growth period for plant (d)

For simplicity, losses from radiological decay during the holdup period[b] and consumption period are neglected. This conservative assumption has no significant impact on the dose contribution, as the radionuclides of interest have long half-lives.

The second stage of the calculation is the estimate of the concentration in plants resulting from resuspension and root uptake. In order to estimate this contribution, the average soil concentration must first be calculated. This linear differential equation is similar to equation 5, with the exception of the loss term.

The loss of contaminants from soil is due to leaching by infiltrating water. This infiltration rate applies only to the effective root zone for plants.

Equations 6 through 9 are necessary in order to determine the loss of contaminants due to leaching [2]. Equation 6 utilizes default data to obtain an estimated infiltration rate.

$$I = \left\{1 - C_e\right\}\left\{\left\{1 - C_r\right\}P_r + I_{rr}\right\} \quad \text{(Eq. 6)}$$

Where:

- I = Infiltration rate (m/year)
- C_e = Evapotranspiration coefficient (dimensionless)
- C_r = Runoff coefficient (dimensionless)
- P_r = Precipitation rate (m/year)
- I_{rr} = Irrigation rate (m/year)[c]

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[b] The holdup period is the time between produce harvest and consumption.

[c] The application rate of irrigation water (L/m^2*d) is related to the annual irrigation rate (m/y) by the crop growing period such that each crop type has a distinct annual irrigation rate.

In order to determine the retardation factor, it is first necessary to calculate the saturation ratio in equation 7.

$$R_s = \left\{I / K_{sat}\right\}^{1/\{2b+3\}} \qquad \text{(Eq. 7)}$$

Where:

- R_s = Saturation Ratio
- K_{sat} = Hydraulic conductivity (m/year)
- b = soil specific exponential parameter [2] [d] (dimensionless)

The retardation factor in equation 8 [2] is the ratio of the pore water velocity to the radionuclide transport velocity.

$$R_d = 1 + \left\{\rho_b * K_d\right\} / \left\{p_t * R_s\right\} \qquad \text{(Eq. 8)}$$

Where:

- R_d = Retardation factor (dimensionless)
- ρ_b = Soil density (g/cm^3)
- p_t = Soil porosity (dimensionless)
- K_d = Distribution coefficient (cm^3/g)

The volumetric water content in equation 9 [2] is the product of the total soil porosity by the saturation ratio.

$$\theta = R_s * p_t \qquad \text{(Eq. 9)}$$

Where:

- θ = Volumetric water content (dimensionless)

Equation 10 [2] is used to obtain a time independent estimate of the leach rate[e] in the root zone as a result of the application of irrigation water and local precipitation.

$$L = I / \left\{\theta * T * R_d\right\} \qquad \text{(Eq. 10)}$$

Where:

- L = Leach rate (y^{-1})
- T = Thickness of contaminated zone (meters)[f]

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[d] The soil-specific b parameter is an empirical parameter used to evaluate the saturation ratio of the soil.

[e] The leach rate calculated is a one dimensional uniform depletion of the uranium from the overall root zone.

[f] The contamination zone in this application is the effective root zone where the uptake of contaminants from plants is of concern.

The area soil density in the root zone thickness is calculated as follows:

$$P_s = p_b * T * 1000 \qquad \text{(Eq. 11)}$$

Where:

- P_s = Areal soil density[g] (kg/m²)
- 1000 = converts the soil density in g/cm^3 to kg/m^3

Having obtained the information necessary to calculate the loss term in the soil, equation 12 [1] calculates the radionuclide deposition rate onto the soil.

$$R_{soil} = \left\{ C_w * IR \right\} / P_s \qquad \text{(Eq. 12)}$$

Where:

- R_{soil} = Average deposition rate onto soil[h] (pCi/kg*d)
- C_w and IR are as defined in Equation 4.

The final concentration at the end of the growing period is shown in equation 13. The modeling uses a time of 50 years of continuous irrigation as the basis for the estimated soil concentration and the resulting calculated release limit[i].

$$C_{soil} = R_{soil} / (L * 365) * \left\{ 1 - e^{-Lt} \right\} \qquad \text{(Eq. 13)}$$

Where:

- C_{soil} = Radionuclide soil concentration at end of growing period (pCi/kg)

Finally, equation 14 calculates the concentration in the plant due to uptake and resuspension [2].

$$C_{plant,uptake+res} = \left\{ ML * F_r + B \right\} * C_{soil} \qquad \text{(Eq. 14)}$$

Where:

- $C_{plant,uptake+res}$ = Radionuclide concentration in plant due to uptake and resuspension (pCi/kg)
- ML = Mass loading factor for resuspension of soil to edible portions of plant (dry weight)
- F_r = Contamination reduction factor from plant surfaces as a result of rinsing and washing.
- B = Concentration factor for uptake of soil to plant (dry weight basis)

The total contaminant concentration in plants, C_{plants}, is the sum of equations 5 ($C_{plant,deposition}$) and 14 ($C_{plant,uptake+res}$). The resulting formula for dose from ingesting contaminated vegetation is as follows:

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[g] The areal soil density is adjusted to reflect the depth of the mass of soil in a given root zone and is plant type specific (i.e. leafy, non leafy, fruit).

[h] The deposition rate to the soil per unit area is converted to the deposition rate to the root volume through the use of the areal soil density. Considering a 50 year application of contamination prior to exposure, a uniform contaminant concentration through the root zone is appropriate.

[i] The equilibrium soil concentration for uranium given the input parameters is well over 1,000 years.

$$Dose_{plants} = \frac{C_{plants}}{27} * Q_{plants} * DCF * F * 10^5 \qquad \text{(Eq. 15)}$$

Where:

- $Dose_{plants}$ = Committed effective dose from ingesting contaminated vegetation (mrem/year)
- C_{plants} = Contaminant concentration in plants from deposition, uptake, and resuspension (pCi/kg)
- Q_{plants} = Intake rate of vegetation (kg/year)
- DCF = 50 year committed effective dose conversion factor for ingestion of contaminants (Sv/Bq)
- F = Fraction of contaminated material that is grown onsite
- 10^5 = Converts Sieverts (Sv) to mrem
- 27 = Converts pCi to Bq

The fraction of contaminated material that is assumed grown in a particular location is 50% for the resident farmer [9]. Given the regional information on home grown production provided in the Exposure Factors Handbook [11], an assumption of 50% is conservative.

RESULTS

In order to identify significant parameters in the conduct of this modeling effort, a sensitivity and uncertainty analysis was performed. A Monte Carlo analysis (Decisioneering 1996) is used to determine the uncertainty surrounding calculated release limit for the resident farmer scenario. The inputs for the Monte Carlo analysis are the probability distributions for key parameters. The distributions used in this analysis are considered subjective, as they are based on the most current information that will be subject to change as more information becomes available in the future.

The shape of the probability distributions reflects the depth of information available for a given parameter [12]. For parameters such as the weathering constant, sufficient data exist to estimate the range and likely value, but insufficient information exists to further define the distribution. The weathering constant is therefore assigned a triangular probability distribution. Greater information exists on the hydraulic conductivity for a given soil type and allows for further definition of the distribution as log-normally distributed, with bounds on the distribution.

A quantitative sensitivity analysis was performed using the data generated during the uncertainty analysis. Using regression techniques, rank correlation coefficients were calculated between each parameter and the uranium release limit. Parameter sensitivities are then established by the degree of correlation between the parameter and the release limit to the resident farmer. The advantage of rank correlation over simple linear correlation is that it is nonparametric. That is, it is not dependent on the underlying distribution of either the input or output variables.

Figure 1 is the output of the Crystal Ball sensitivity analysis for all modeled parameters. Figure 1 shows that only a handful of parameters significantly impact the final result.

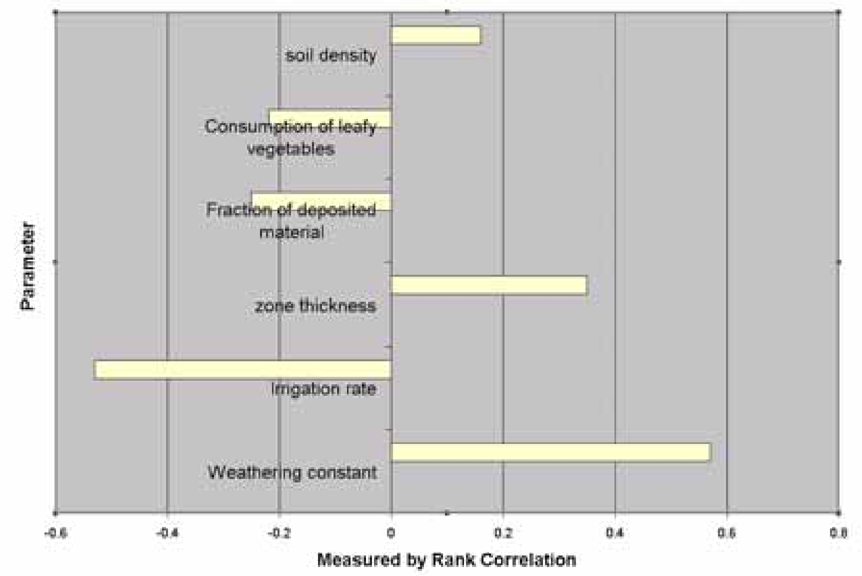

Fig. 1. Sensitivity analysis results

The most significant parameter is the weathering constant. The implication of this parameter are that a larger weathering constant results in greater contaminant removal and therefore leads to a higher allowable release limit. The possible range for this parameter is adequately modeled as the informational review in Till's Radiological Assessment book support the range provided by NUREG 6997. Had a trickle irrigation system been applied, this entire pathway would have been removed and would have significantly increased the ARL.

The second most significant parameter is the irrigation rate. Increases in the irrigation rate results in a larger amount of contaminants deposited on the plants and soil leading to a decrease in the allowable release limit. The upper bound on the irrigation rate is estimated as 20% greater than the 2.5 cm week^{-1} recommended by the Payne County horticulturalist. The lower bound is calculated from actual evapotranspiration data from Stillwater, Oklahoma and matched to the long term precipitation rate for the same area. The resulting lower bound irrigation rate was also adjusted for the type of crop (leafy, non leafy, fruit).

The zone thickness for non leafy vegetables is positively correlated meaning that as the depth of the roots increase the allowable release limit increases as well.

Fraction of deposited activity initially retained on plant surfaces (leafy vegetables). A weak negative correlation. A greater amount of activity retained on plant surfaces directly results in an increase in the overall contamination on the plant and a lower allowable release limit.

Consumption rate for non leafy vegetables. A weak negative correlation that indicates that increases in the consumption rate result in a greater uptake of contaminants and a lower allowable release limit.

The soil density plays a modest role in the predicted release limit. Changes in the soil density has two competing effects. The first, and smaller effect is the impact to the predicted leach rate. Essentially, a greater soil density results in a larger retardation factor which in turn results in a smaller leach rate. The smaller leach rate results in a higher soil concentration and therefore a greater plant concentration and lower overall release limit. The second and greater effect, is that increases in the soil density result in an increase in the overall areal soil density. The increased mass in the root zone as a result of the increase in soil density results in an overall decrease in the contaminant concentration in the soil, the net effect of this is an increase in the allowable release limit. Given a rank correlation coefficient of 0.16, soil density plays a minor role in the allowable release limit. All other parameters have less than a ±0.1 correlation coefficient.

Figure 2 displays the distribution of the ARL to the resident farmer. The distribution is a positively skewed log normal distribution that is peaked at the median value with a kurtosis of 5.5. The median value of the distribution is 28 Bq L^{-1} (770 pCi L^{-1}) and the mean value is 30 Bq L^{-1} (820 pCi L^{-1}).

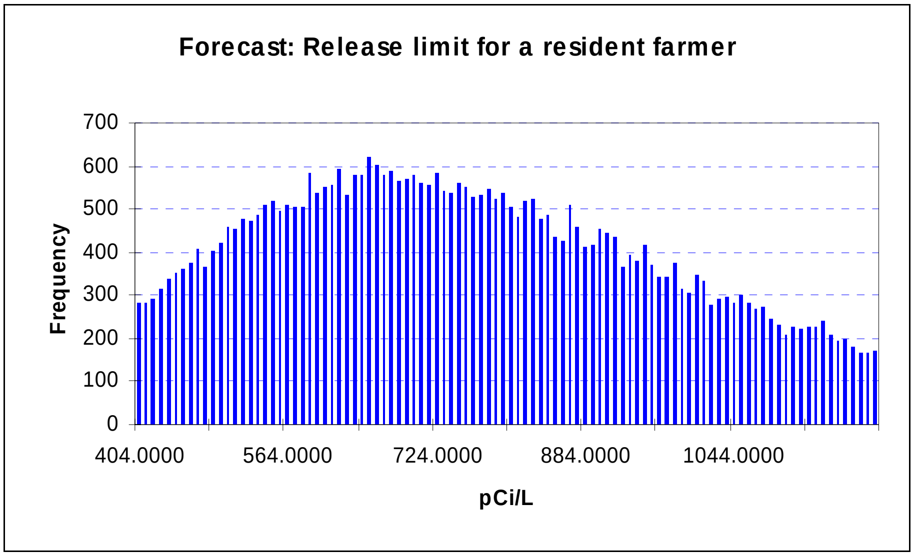

Fig. 2. Uncertainty analysis results

Considering that the endpoint of interest for this analysis is the average member of the critical group, the predicated average release limit of 30 Bq L^{-1} appears to be the appropriate basis for consideration.

SUMMARY

The derived ARL for total uranium in groundwater is 30 Bq L^{-1} (820 pCi L^{-1}). This proposed ARL was derived from the dose conversion factor of 0.0082 mSv yr^{-1} Bq^{-1} L (3.04E-02 mrem yr^{-1} pCi^{-1} L) total uranium, and translates to a dose of 0.25 mSv yr^{-1} (25 mrem yr^{-1}) to the resident farmer from all reasonable exposure pathways. These determinations were made with the realistic assumption that the Vanoss Group would not be used as a source for drinking water and could only supply the required volume of water to serve as the water source for the plant pathway.

REFERENCES

1. Kennedy, W.E., Jr. and D.L. Strenge, Residual Radioactive Contamination from Decommissioning: Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivale*nt*, NUREG/CR-5512, PNL-7994, Washington, D.C., 1992.
2. Yu, C., A.J. Zielen, J.J. Cheng, Y.C. Yuan, L.G. Jones, D.J. LePoire, Y.Y. Wang, C.O. Loureiro, E. Gnanapragasam, E. Faillace, A. Wallo III, W.A. Williams, and H. Peterson, Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.61, ANL/EAD/LD-2, Argonne National laboratory, Argonne, Illinois, 1993.
3. Yu, C., LePoire, D., Gnanapragasam, E., Arnish, J., Kamboj, S., Biwer, B.M., Cheng, J.-J., Zielen, A., and Chen, S.Y. Development of Probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 Computer Codes, NUREG/CR-6697, Argonne National Laboratory, 2000.
4. Lower, S.R. Conceptual Hydrogeologic Model for the Kerr-McGee Corporation Cushing Remediation Site. July 2001.
5. Thomas, J. Upper Vanoss Yield. Enercon Services, Inc. 2003.
6. ICRP, Age-Dependent Doses to Members of the Public From Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Dose Coefficients, ICRP Publication 72, Oxford, Pergamon Press, 1995.
7. Till, J.E. and H.R. Meyer, Radiological Assessment: A Textbook on Environmental Dose Analysis, NUREG/CR-3332, Washington, D.C., 1983.
8. Decisioneering, Inc., Crystal Ball: A Forecasting and Risk Analysis Program, version 4.0, Boulder, Colorado, 1996.
9. U.S. NRC. Policy and Guidance Directive PG-8-08: Scenarios for Assessing Potential Doses Associated with Residual Radioactivity. 1994.
10. Eckerman, K.F., and J.C. Ryman, External Exposure to Radionuclides in Air, Water, and Soil, Federal Guidance Report No. 12, U.S. EPA, Washington D.C., 1993.
11. U.S. EPA, Exposure Factors Handbook, U.S. EPA/600/P-95/002, Washington, D.C., 1997.
12. NCRP, A Guide for Uncertainty Analysis in Dose and Risk Assessments Related to Environmental Contamination, NCRP Commentary No. 14, 1996.