Paper

IN VITRO DISSOLUTION OF URANIUM-CONTAMINATED SOIL IN SIMULATED LUNG FLUID CONTAINING A PULMONARY SURFACTANT

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Abstract—**During the latter part of the twentieth century, the United States developed a highly technical nuclear weapons complex that involved workers at many facilities performing complex missions at a number of different industrial sites across the country. Now, many of these sites are being remediated to remove legacy materials including chemical and radioactive wastes. Along with remediation comes the responsibility to adequately assess risk to cleanup workers who could be exposed to any hazardous materials, including resuspended uranium dust, encountered during environmental restoration. Inhalation of resuspended uranium represents one of the exposure hazards at an abandoned former metal rolling mill where approximately 11 thousand tons of uranium metal was rolled between 1947 and 1958. Residual uranium contamination in the dirt floor of this abandoned site has been exposed to rain, ice, snow, and other environmental factors for more than 50 y. This report describes the solubility of the uranium contamination in this dirt measured in vitro using a modified recipe for simulated lung fluid that contains a pulmonary surfactant. Small (0.1 g) aliquots of dirt collected at this site were sequentially dissolved in simulated lung fluid for increasing periods of time up to 30 d. Solubility was classified according to the ICRP categories as fast, medium, and slow. Results demonstrate that the solubility designation for the uranium contamination in the dirt is approximately 50% fast, 15% medium, and 35–40% slow. There was no observed difference in solubility when a pulmonary surfactant was added to the simulated lung fluid.**
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Key words: contamination; exposure, occupational; lungs, human; radioactivity, residual

INTRODUCTION

THE OBJECTIVE of this research was to determine the in vitro solubility of uranium contamination present in the dirt floor of an abandoned metal rolling mill that will be remediated some time in the future. Another objective was to investigate whether the addition of a pulmonary surfactant to the conventional formulation for simulated lung fluid would affect in vitro solubility. During remediation, it is likely that uranium contamination in the dirt floor could be resuspended and constitute an occupational or environmental exposure hazard. A sample of dirt contaminated with uranium was collected from the dirt floor of an abandoned mill that rolled approximately 1.3×10^7 kg uranium metal stock in the 1940s and 1950s (Glassford et al. 2013). The solubility of uranium is an important factor in predicting the fate of the contamination in the environment and risk to humans (Till and Meyer 1983; Eisenbud 1987; Elless et al. 1997; Eidson 1994). A series of experiments was performed using a standard recipe for simulated lung fluid (SLF) modified by the addition of a pulmonary surfactant. It was proposed that metals bound to the surfactant would interact with lysosomes in pulmonary alveolar cells such that the rate of uranium dissolution would differ from that measured without surfactant (Berry et al. 1988).

Background

Throughout most of the latter half of the twentieth century, the U.S. Department of Energy (DOE) used multiple sites around the United States to develop nuclear materials for defense. Activities at these sites were highly varied, starting with uranium ore and ending with the assembly and testing of components for nuclear weapons. Many of these legacy sites have long since been repurposed or retired, including those used for metal processing and fabrication. During the very early period of the Manhattan Project, regulations to control emissions of radioactive materials, including uranium, were less rigorous than those of today. The U.S. Environmental Protection Agency (EPA) has cited more than 1,500 hazardous waste sites within the United States on the National Priorities List (NPL), also known as

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Superfund waste sites, some of which were part of the nuclear weapons complex (USEPA 2011).

While several legacy facilities have been decontaminated and plans have been developed for others, residual uranium contamination at an abandoned former metal rolling mill offers a unique opportunity to determine the solubility of residual uranium metal contamination present in the dirt floor of the mill. The literature contains results of many studies of uranium solubility in simulated lung fluid and environmental media to elucidate risk to human health (Elless et al. 1997; LaMont et al. 2001; Dennis et al. 1982; Heffernen et al. 2001; Metzger et al. 1997). The source of the uranium contamination in the dirt floor at this site was associated with the physical process of rolling over 11 thousand tons of hot-forged uranium metal during the late 1940s and 1950s. The windows, doors, and roof of this abandoned facility are severely damaged, permitting entry of rain, snow, ice, and small rodents. Approximately 3 kg of the dirt floor near one of the large rolling mills was collected to determine the solubility of the uranium contamination after contact with soil and exposure to environmental conditions for over 50 y. This legacy contamination also represents an excellent material for nuclear forensics training since the processes that generated the uranium metal and the contamination at the rolling mill are well known (FUSRAP-Guterl 2010). The particle size distribution of the uranium contamination in this material was previously evaluated (Glassford et al. 2013).

Solubility and pulmonary surfactants

There are many reports describing the dissolution of various forms of uranium in the respiratory tract (Mercer 1967; Cooke and Holt 1974; Chazel 1998; Eidson and Mewhinney 1980; Eidson and Griffith 1984; Eidson 1994). Likewise, many clinical studies have been performed regarding the significance of pulmonary surfactants for treatment of respiratory disease (Wright 2003; Whitsett et al. 2010; Devendra and Spragg 2002). One hypothesis adopted in this research was that a pulmonary surfactant could affect the dissolution of uranium particles in the respiratory tract because evidence has been documented of lysosomes in certain surfactants concentrating and interacting with heavy, toxic metals (Berry et al. 1988).

The focus of the cited reports on the dissolution of uranium in the respiratory tract include studies of (1) different uranium compounds, (2) uranium produced at uranium mills, (3) uranium produced at industrial sites, and (4) uranium produced at processing plants. No studies were found that investigated whether a pulmonary surfactant would affect in vitro solubility of uranium. Therefore, as part of this research project, the conventional recipe for simulated lung fluid was modified to incorporate a pulmonary surfactant that is commonly used to treat pneumothorax and acute atelectasis, especially in neonates (Lee 2012; Wedding and Gylys 2005).

Composition and function of pulmonary surfactants

The alveolar region of the lung is where the majority of oxygen and carbon dioxide gas exchange between the lung and blood occurs (Wright 2003). A thin epithelium covering the surface of the alveoli is lined by type I and type II alveolar epithelial cells that are in contact with respiratory gases. These cells provide a region for air-liquid interactions (Whitsett et al. 2010). Type I epithelial cells comprise the wall of the alveolus, while Type II epithelial cells are scattered within the alveolar walls and are found at intersecting points of multiple alveoli where they serve as a reserve for producing and repairing damaged surfactant (Caceci 2012).

Surfactants (surface active agents) are molecular agents that are typically amphiphilic organic compounds that exhibit both hydrophilic and lipophilic properties. One end of the surfactant molecule is hydrophilic and adheres to areas where gases and liquids meet, while the other end is hydrophobic, usually a hydrocarbon, and interacts with other hydrophobic substances in air, such as bacteria or oil-like material (Furse 2012). For example, soaps or detergents are consumer products that contain surfactants that are used to clean hydrophobic substances, similar to the purpose of a pulmonary surfactant in the lungs.

Pulmonary surfactant is an essential, lipid-rich coating found on the walls of the alveoli, which enables expansion and contraction by reducing surface tension of the aqueous film surrounding the cells and lessens the intermolecular attraction of water molecules (a hydrophobic barrier). Without surfactant present at the air-capillary barrier, the collapsing forces of the lung would render the alveoli nonfunctional (Whitsett et al. 2010). Various proteins are found in this surfactant that offer a defense against foreign bodies and pulmonary inflammation. Some of these proteins interact with macrophages to carry out these functions through phagocytosis (Wright 2003). Macrophages are free cells within alveolar lumen and serve as phagocytic sterilizers. These macrophages provide protection of the deepest part of the lung, especially when dust particles or bacteria reach beyond the upper regions of the respiratory tract.

The respiratory tract is an elaborately branched, tubular structure that culminates into roughly 300 million alveolar sacs. Type II epithelial cells are critical providers for surfactant fabrication, provide repairing capabilities following injury, and also generate type I epithelial cells, which reside over the majority of the gas-exchange region of the alveoli (Whitsett et al. 2010).

Pulmonary surfactants have three general components: phospholipids (80%), proteins (10%), and neutral lipids (10%). Surfactant proteins (SP) are comprised of four

components: SP-A, SP-B, SP-C, and SP-D, each having a specific task (Wright 2003; Ikegami et al. 2005). SP-A and SP-D provide defense properties, while SP-B and SP-C are incredibly hydrophobic, interacting with the phospholipids in surface tension stabilization (Devendra and Spragg 2002). The roles of SP-A and SP-D, along with some of the physical properties of surfactant in general, may have a role in affecting the dissolution rate of particles deposited in the respiratory tract.

The pulmonary surfactant added to the conventional recipe for simulated lung fluid is a natural bovine lung extract, SURVANTA® (beractant), that is commonly used to treat Infant Respiratory Distress Syndrome (IRDS) and Acute Respiratory Distress Syndrome (ARDS) (SURVANTA® 1999; Blanco and Perez-Gil 2007). Although SURVANTA® does not contain SP-A, it does contain SP-B and SP-C. Since this surfactant is manufactured to prevent and control ARDS, the presence of surface tension active protein rather than alveolar defense proteins is understandable. However, the hydrophobic proteins may not fully mix with the high water volume of the SLF, a potential concern in this experiment.

Berry et al. (1988) studied whether toxic mineral elements, such as chromium, cerium, uranium, or other readily and slightly soluble materials become concentrated in specific areas of the body, especially the pulmonary region of the respiratory tract. It was reported that toxic heavy metals are not transported from deposition sites in the alveolar region of the lung into the blood stream but accumulate within the lysosomes found in pulmonary alveolar cells. Toxicity of a material is significantly dependent on its solubility. Insoluble materials reaching the pulmonary alveoli may also be engulfed by macrophages. Alternatively, the material may cross the alveolar-capillary barrier and be transported to other areas of the body, which have an affinity for heavier materials (e.g., bone). An interactive mechanism for toxic metals in the respiratory tract involves clearance of material isolated by lysosomes from the alveoli. For example, pulmonary lysosomes, such as type I pneumocytes, macrophages, and lysosomal hydrolases, will concentrate toxic substances, like uranium. One or more of these mechanisms may affect in vitro dissolution of the uranium metal contamination present in samples of dirt evaluated in this research.

A second group of very small, clay-like inhaled insoluble particles can reach the alveoli and concentrate in the macrophages. The difference occurs when lysosomal hydrolases slowly dissolve the minerals that may be released and transported through alveolar clearance. Some toxic elements bind to cerebral tissues, causing incurable cerebral lesions (Roberts 1986). Inhaled water-soluble toxic particles, such as iodine, diffuse rapidly across the alveolar-capillary barrier and into target organs. Alternatively, alveolar clearance of such particles would involve being captured by lysosomes of alveolar macrophages where the dissolved particles concentrate. If toxic substances are concentrated by macrophages, they cannot spread to target organs but instead are slowly eliminated through alveolar clearance (Berry et al. 1988).

The complex, diverse physical arrangement of the respiratory tract makes it challenging to describe the transport and dissolution of inhaled particles. If SP-A and SP-D treat inhaled particles of uranium metal as foreign bodies in the alveolus, then dissolution of uranium should be affected by these protein interactions. It becomes a question whether the surfactant traps and isolates toxic metals, like uranium, or expels them through an alveolar clearance mechanism. It is also necessary to consider how well a surfactant will interact with components of the conventional SLF.

The objective of this research was to determine the dissolution rate of uranium metal contamination in SLF and whether the addition of a pulmonary surfactant makes any significant difference in the observed solubility. The formulation for SLF and the dissolution method used in this study was previously reported by Heffernen et al. (2001). A natural bovine lung extract pulmonary surfactant was added to the SLF formulation for some of the samples tested in this research. Samples were sequentially exposed to SLF for increasing periods of time from 1 h up to 30 d. The measured rate of dissolution was evaluated relative to (F-fast), (M-moderate), and (S-slow) categories adopted by the International Commission on Radiation Protection (ICRP 1991). These categories are analogous to former categories (D-days), (W-weeks), and (Y-years) (ICRP 1982). The model of the human respiratory tract (ICRP 1994) provides parameter values for the F, M, and S absorption/dissolution types and discusses the fate of uranium upon entering the blood stream and removal half-times from the body as a whole.

MATERIALS AND METHODS

Table 1 lists the formulation used in this research for the simulated lung fluid (SLF). A pulmonary surfactant was added to the SLF for half of the samples tested to

Table 1. Material composition of the simulated lung fluid used in this project (Moss 1979; Heffernen et al. 2001).

Chemical	Formula	Concentration (g L^{-1})
Magnesium chloride	$MgCl_2 \cdot 6H_2O$	0.2067
Sodium chloride	NaCl	6.0193
Potassium chloride	KCl	0.3017
Sodium phosphate, dibasic	$Na_2HPO_4 \cdot 7H_2O$	0.2681
Sodium sulfate	Na_2SO_4	0.0711
Calcium chloride	$CaCl_2 \cdot 2H_2O$	0.3697
Sodium acetate	$NaH_3C_2O_2 \cdot 3H_2O$	0.9528
Sodium bicarbonate	$NaHCO_3$	2.6115
Sodium citrate	$Na_3H_5C_6O_7 \cdot 2H_2O$	0.0981

Table 2. Identification and characteristics of samples analyzed in this project.

Sample IDs	Solvent	Soil mass (g)
A	100% SLF	0.1020
B	100% SLF	0.1064
CRMSLF	100% SLF	0.1066
BSLF	100% SLF	Blank, No Soil
C	98% SLF,2% Surfactant	0.1153
D	98% SLF, 2% Surfactant	0.1086
CRMSUR	98% SLF, 2% Surfactant	0.1066
BSUR	98% SLF, 2% Surfactant	Blank, No Soil
PB	Tracer Blank	U Separation Only
QC	Quality Control	U Separation Only

determine whether the surfactant affects the rate of dissolution of uranium. Four samples, each containing approximately 100 mg of uranium-contaminated dirt, were subjected to dissolution testing. Two of the samples were dissolved in the standard formulation for SLF. Two other samples were dissolved in 98% SLF plus 2% SURVANTA® pulmonary surfactant. A uranium standard and blank were included with each of the dissolutions. Table 2 identifies each of the 10 samples analyzed in this research. Before dissolution, the uranium content in each sample was determined qualitatively using gamma spectrometry since the uranium contamination is not homogeneously distributed in the dirt floor (Glassford et al. 2012). All components and containers used in making simulated lung fluid were sterilized to prevent growth of mold and bacteria. The SLF was sterilized by micro-filtration using a 0.22 μm syringe filter. The surfactant was sterilized by the manufacturer.

The uranium-contaminated dirt was added to 100 mL of SLF in a 250 mL polyethylene bottle. This arrangement provides good sample-solvent contact with adequate solvent to dissolve the uranium. The pH of the solvent was controlled between 7.2–7.4 by bubbling of CO_2 gas through the solvent as needed throughout dissolution testing. The samples were maintained at 37°C using a shaker bath. After each dissolution period, samples were centrifuged for 30 min, the supernatant was removed using a pipet, and the sample was acidified with concentrated HNO_3 to keep uranium in solution (Briant and James 1990). Fresh SLF (or SLF plus surfactant) was added to each of the decanted samples to initiate the next period of dissolution. No additional surfactant was added since contact with the uranium was expected to be complete within the first hour. The fractional dissolution periods were 1 h, 4 h, 8 h, 24 h, 7 d, and 30 d and were selected because they are consistent with type F and M solubilities. Any remaining undissolved uranium after 30 d was considered as type S and was completely dissolved for analysis using a rigorous potassium fluoride and pyrosulfate fusion to remove silicates, iron, and other interfering species (Sill 1987). Blank samples were not fused.

The precise content of uranium in each of the dissolution fractions was determined by using anion exchange chromatography to extract uranium from the solvent. A precisely known quantity of ^{232}U tracer was added to each fraction to determine the chemical yield. Uranium from each fraction was eluted from the ion exchange resin and electroplated onto stainless steel planchets. Alpha spectrometry was used to measure alpha particle energies. The minimum detectable activity (MDA) for alpha spectrometry was approximately 0.030 dpm (disintegrations per minute). Samples measured by alpha spectrometry are limited to an activity less 50 dpm to avoid degrading spectral resolution. The size of each sample aliquot submitted for alpha spectrometry was first pre-determined by gross alpha counting 1 mL of each fraction using a liquid scintillation counter. The total quantity of uranium contained in each sample is determined by adding the amount in each dissolution fraction plus the amount of uranium dissolved in the fusion. The rate of uranium dissolution is the fraction of the total uranium dissolved in each dissolution period.

Alpha spectrometry measurements were performed within 3 d after separation and electrodeposition to avoid interference from the ingrowth of progeny. Each planchet was measured for 1,000 min approximately 0.5 mm from the face of the silicon detector. A thin collodion film was placed over each planchet to minimize contamination of the detector by recoil nuclei (Inn et al. 2008; Sill and Olson 1970).

RESULTS

The isotopic composition of the uranium contamination in the dirt appears to be of natural origin based upon the ratio of ^{238}U to ^{235}U alpha activity. However, the history of the mill indicates that a small quantity of depleted and some enriched, recycled uranium was also rolled. Therefore, the concentration of uranium in each of the dissolution fractions was determined by measuring the isotopic uranium activity on each of the electrodeposited planchets using alpha spectrometry. The alpha energies of interest are associated with ^{238}U at 4.197 MeV, ^{234}U at 4.776 MeV, ^{235}U at 4.398 MeV, and the tracer ^{232}U at 5.320 MeV.

Tables 3 and 4 list results of the ^{238}U concentration measured in each of the dissolution fractions for the contaminated dirt and SRM, respectively. Figs. 1–4 show the fractional dissolution of uranium from each of the four samples of uranium-contaminated dirt. SigmaPlot™ (2008) was used to determine the best-fit, nonlinear regression function using results for ^{238}U measured in each dissolution fraction that describes the fractional rate of dissolution of uranium for each sample of dirt. A three component, exponential function in the form $F(t) = Ae^{-kt} + Be^{-lt} + Ce^{-mt}$,

Table 3. Results of ^{238}U measured in each of the six dissolution fractions (1, 4, 8, 24 h, 7, and 30 d) and the residual (i.e., undissolved) uranium for each sample of uranium-contaminated dirt. The quantity of uranium in the undissolved fraction was determined by fusion. The sum of ^{238}U measured in each fraction plus the undissolved fraction is also listed.

SLF A Fraction #	^{238}U (Bq)	Uncertainty (%)	SLF+SUR C Fraction #	^{238}U (Bq)	Uncertainty (%)
A1	12.2	3.7	C1	14.8	3.5
A2	1.78	5.0	C2	3.92	3.7
A3	1.38	5.6	C3	1.37	6.2
A4	1.17	6.1	C4	1.85	5.2
A5	2.04	4.7	C5	2.05	5.0
A6	4.73	5.6	C6	3.50	5.6
Fusion A	8.75	3.6	Fusion C	16.9	3.3
Total ^{238}U	32.0	1.9	Total ^{238}U	44.3	1.8
SLF B Fraction	^{238}U (Bq)	Uncertainty (%)	SLF+ SUR D Fraction #	^{238}U (Bq)	Uncertainty (%)
B1	12.2	4.5	D1	12.0	3.8
B2	2.51	4.3	D2	3.97	3.9
B3	1.03	6.8	D3	1.77	5.5
B4	1.35	3.2	D4	1.59	5.6
B5	2.27	4.8	D5	3.50	4.2
B6	5.01	4.8	D6	3.40	5.3
Fusion B	11.8	3.3	Fusion D	16.4	3.3
Total ^{238}U	36.2	2.1	Total ^{238}U	42.7	1.8

describes the undissolved fraction of uranium in each sample with time, *t*. Correlation was in excess of 0.9999 for each sample. The coefficients (A, B, and C) and exponents (k, l, and m) of each exponential in this function are the fractions and dissolution rate constants for each component, respectively. There is no apparent statistical difference in the fractional dissolution between samples dissolved in the conventional SLF or the SLF containing a pulmonary surfactant. Results demonstrate that the solubility designation for the uranium contamination in the dirt is approximately 50% fast, 15% medium, and 35–40% slow. In comparison, the fractional dissolution for the standard reference material NBL CRM 129 U_3O_8 is approximately 100% slow.

The major source of measurement uncertainty was associated with alpha spectrometry, which contributed approximately 5% uncertainty to the final result. Variations in aliquot and tracer dispensing did not exceed 10^{-4}. Summation of total error for a given fraction was determined through the function:

$$\left(\sigma_f/f\right)=\left[\left(\sigma_A/A\right)^2+\left(\sigma_B/B\right)^2+\left(\sigma_C/C\right)^2_{...}\right]^{1/2},$$

where σ represents the standard deviation of a value, and A, B, and C reflect specific points of uncertainty. The quantity of uranium in all fractions exceeded the minimum detection limit of approximately 0.030 dpm sample^{-1}. Tracer recovery ranged from 49.4% to 91.8%.

DISCUSSION

Adding a pulmonary surfactant to the recipe for simulated lung fluid appears to make no statistical difference in

Table 4. Results of ^{238}U measured in each of the six dissolution fractions (1, 4, 8, 24 h, 7, and 30 d) and the residual (i.e., undissolved) uranium for each sample of the uranium oxide U_3O_8 certified reference material CRM 129. The quantity of uranium in the undissolved fraction was determined by fusion. The sum of ^{238}U measured in each fraction plus the undissolved fraction is also listed.

SLF E CRM	^{238}U (Bq)	Uncertainty (%)	SLF+SUR F CRM	^{238}U (Bq)	Uncertainty (%)
E1	0.625	11.8	F1	0.80	10.6
E2	0.252	11.0	F2	0.364	9.9
E3	0.174	14.2	F3	0.133	16.5
E4	0.719	7.6	F4	0.276	11.3
E5	1.54	5.5	F5	1.81	4.8
E6	11.1	3.5	F6	4.87	4.3
Fusion E	964	3.2	Fusion F	993	3.3
Total ^{238}U	979	3.1	Total ^{238}U	1001	3.3

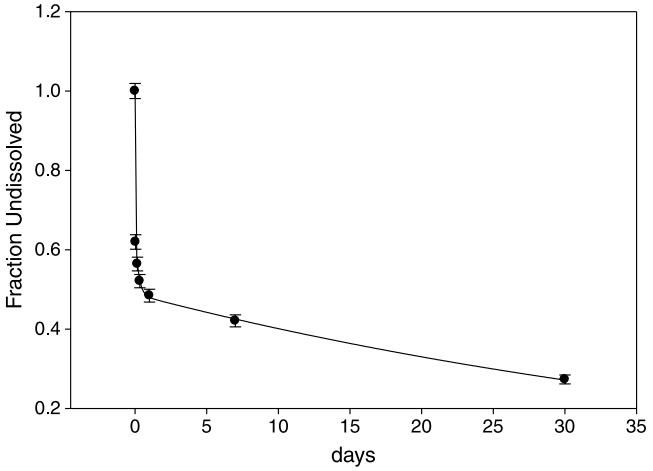

Fig. 1. Remaining fraction, f, of uranium in sample A undissolved with time in simulated lung fluid, where $f = 0.354e^{-597t} + 0.158e^{-4.30t} + 0.488e^{-0.0194t}$.

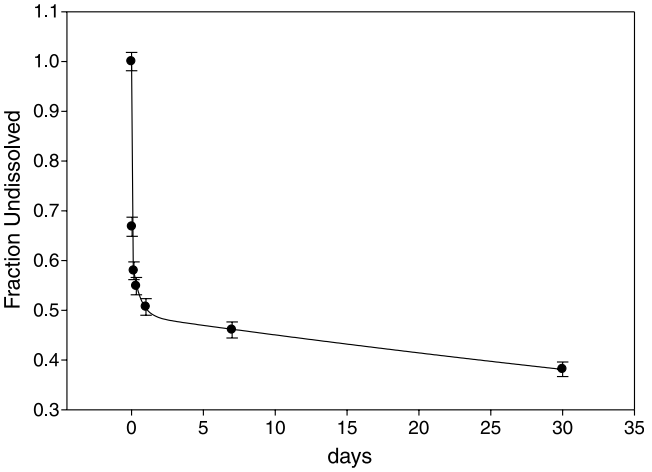

Fig. 3. Remaining fraction, f, of uranium in sample C undissolved with time in simulated lung fluid containing a pulmonary surfactant, where $f = 0.390e^{-42.1t} + 0.120e^{-1.88t} + 0.490e^{-0.00836t}$.

the dissolution of uranium from the soil. Measurement uncertainties and the heterogeneity of uranium metal contamination in the bulk soil more than account for any differences in the fractional dissolution. Furthermore, several different methods were used in hot forging uranium metal stock before rolling, which could alter surface metallurgy, especially after being exposed to ambient environmental conditions for over 50 y. Although uranium metal is the expected elemental form for the contamination, some of the variation in solubility among all the samples may be due to the presence of UO_2 and U_3O_8. However, the large fraction of rapidly soluble uranium suggests that a significant component of the uranium contamination is in the form of a well-oxidized U^{6+} metal. In contrast, analysis of samples containing NBL CRM 129 confirms that pure U_3O_8 is very insoluble. Oxidized uranium metal present in soil arising from one of several rolling methods is now likely in the form of $U^{6+}O_2$, which confirms the observation for the large, rapidly soluble component. That is not to rule out the site operations contributing to the overall U^{6+} concentrations in tandem with the slow oxidation of UO_2.

Dose conversion factors obtained using the computer program RESRAD 6.5 (2009) were used to determine the potential radiation dose and risk associated with exposure to uranium contamination observed at this abandoned facility. Dose rates per unit intake (Bq) are 2.59 mrem, 0.95 mrem, and 0.158 mrem for S, M, and F class solubility, respectively.

CONCLUSION

The dissolution rates, as determined by the three component (six-parameter) exponential functions, provide credible insight into the nature of the uranium metal contamination present in this soil. There is no apparent

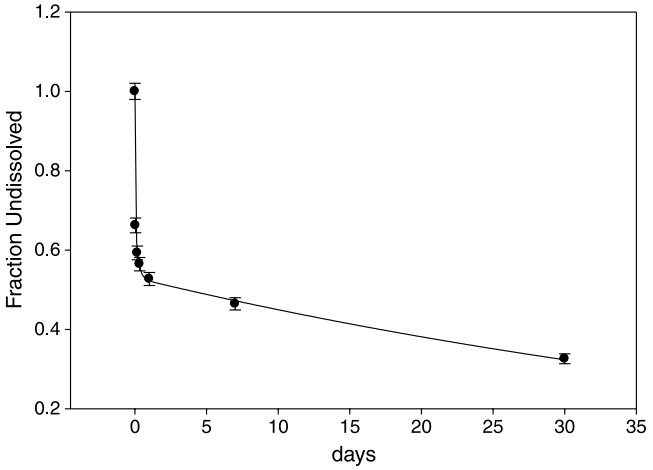

Fig. 2. Remaining fraction, f, of uranium in sample B undissolved with time in simulated lung fluid, where $f = 0.310e^{-1398t} + 0.158e^{-4.89t} + 0.530e^{-0.0165t}$.

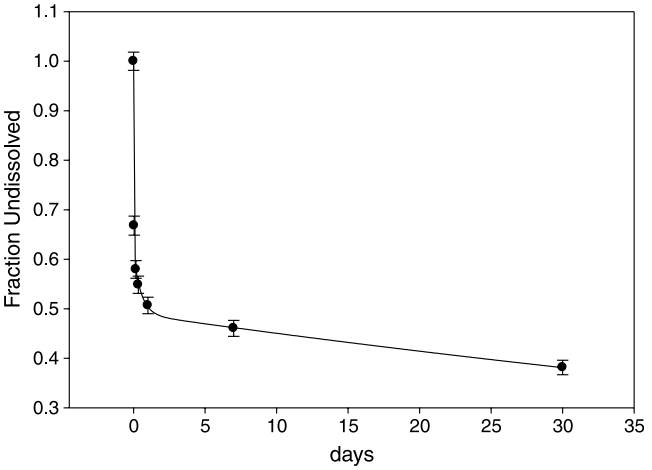

Fig. 4. Remaining fraction, f, of uranium in sample C undissolved with time in simulated lung fluid containing a pulmonary surfactant, where $f = 0.362e^{-34.5t} + 0.146e^{-1.01t} + 0.492e^{-0.00830t}$.

difference in the measured dissolution rates with the addition of a pulmonary surfactant to the conventional formulation for simulated lung fluid. After oxidation and weathering for more than 50 y, the uranium contamination present in the soil at this abandoned rolling mill appears to exhibit a significantly soluble fraction that should be considered when determining worker safety guidelines for site remediation. Results of this study provide health physicists and engineers with technical guidance for establishing appropriate protective measures to avoid unnecessary risk for workers and the environment. Further studies include analysis of the solubility associated with the respirable fraction of this contaminated soil and whether a different quantity or type of pulmonary surfactant can alter the dissolution. The physical and chemical characteristics associated with the uranium contamination in the soil provide the nuclear forensics professional with a basis for interpreting what type of process generated the observed contamination.

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