

Health Risk Assessment and ALARA Analysis in Support of Alternative Concentration Limit Application for Mine Unit 1

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1 INTRODUCTION

This report is written in support of an Alternative Concentration Limit (ACL). See the General Information section of the cover document for the Mine Unit 1 application.

2 HAZARD ASSESSMENT

2.1 Source and Contamination Characterization

Potential effects of restored Mine Unit 1 groundwater on downgradient groundwater chemistry have been investigated. Enchemica (2017) summarizes production and restoration history of Mine Unit 1 as well as the pre-ISR and current post-restoration aquifer sediment chemistry and groundwater quality conditions. Site-specific data were used to develop a one-dimensional groundwater transport model using the PHREEAQ computer code to predict the effects of groundwater transport from Mine Unit 1 point of compliance (POC) wells to downgradient point of exposure (POE) wells. Results are described in Enchemica (2017) sections 4 and 5.

The transport modeling results show that pH of the groundwater and concentrations of uranium, arsenic, selenium and radium-226 at the Point of Exposure (POE) locations will not be significantly affected by transport from the Mine Unit 1 production zone because of attenuation by downgradient reducing sediments. Total dissolved solids, magnesium and iron concentrations might occur at the POE locations within the modeled 1,000-year period.

2.2 Constituents of Concern

COCs have been identified in groundwater based on the approved NRC License SUA 1548, WDEQ Permit and Criterion 5B(2) of Appendix A to 10 CFR Part 40. COCs in groundwater at the Site were defined by comparing post-restoration data to the calculated baseline UTLs and the MCVs presented in Criterion 5C. Based on data provided by Cameco Smith Ranch (CSR), the only constituents of concern for Mine Unit 1 (MU-1) are uranium, arsenic and selenium. Radium is not considered a constituent of concern because total radium concentrations at the POC are indistinguishable from or below baseline values.

2.3 Health and Environmental Risks of Constituents

2.3.1 Uranium

Uranium is assumed to be carcinogenic due to its radioactive emissions, but is primarily regulated due to its nephro-toxicological effects. As stated in ATSDR (2013), "Current evidence from animal studies suggests that the toxicity of uranium is mainly due to its chemical damage to kidney tubular cells following exposure to soluble uranium compounds and the respiratory tract following chronic inhalation exposure to insoluble uranium compounds. Other potential targets of toxicity include the reproductive system and the developing organism. There are limited data on the renal toxicity of uranium

following inhalation exposure in humans. A number of studies found no alterations in mortality due to renal disease in uranium workers. An autopsy study of long-time workers exposed to low levels of uranium did not find evidence of renal injury years after exposure termination.”

2.3.2 Arsenic

Inorganic arsenic has been recognized as a human poison for centuries. Oral doses greater than 60 ppm in water can result in death. Lower levels of inorganic arsenic, ranging from about 300 to 30,000 ppb in water may result in irritation of the stomach and intestines, with symptoms such as stomachache, nausea, vomiting, and diarrhea. Other effects that might occur from swallowing inorganic arsenic include decreased production of red and white blood cells, which may cause fatigue, abnormal heart rhythm, blood-vessel damage resulting in bruising, and impaired nerve function causing a “pins and needles” sensation in hands and feet.

A characteristic effect of long-term oral exposure to inorganic arsenic is a pattern of skin changes that include patches of darkened skin and the appearance of small “corns” or “warts” on the palms, soles, and torso, and are often associated with changes in the blood vessels of the skin. Skin cancer may also develop. Ingestion of arsenic has been reported to increase the risk of cancer in the liver, bladder, and lungs.

Direct skin contact with high concentrations of inorganic arsenic compounds, may irritate the skin causing some redness and swelling. It does not appear that skin contact is likely to lead to any serious internal effects.

Groundwater at the site is not expected to contain organic arsenic attributable to Smith Ranch operations. There is virtually no information available on the effects of organic arsenic compounds in humans. Animal studies show that most simple organic arsenic compounds (such as methyl and dimethyl compounds) are less toxic than the inorganic forms. Ingestion of methyl compounds by animals can result in diarrhea.

2.3.3 Selenium

Selenium is an essential element in trace quantities. However, at excessive levels, selenium may be toxic to humans. The adverse health effect of exposure to selenium is limited to systemic toxicity. Selenium is not known to be a carcinogen. According to the ATSDR Toxicological Profile for selenium “a minimum dietary level of selenium is required for good health” (ATSDR, 2003). ATSDR also states that “Even if mildly excessive amounts of selenium are eaten over long periods, brittle hair and deformed nails can develop. In extreme cases, people may lose feeling and control in arms and legs.” (ATSDR, 2003).

Selenium is ubiquitous in the environment, being released from both natural and anthropogenic sources. Combustion of coal results in the principal releases of selenium into the environment as a consequence of human activities. Exposure pathways of the general population are highest in food, followed by water and air.

As stated by (ATSDR, 2003)

The primary factor determining the fate of selenium in the environment is its oxidation state. Selenium is stable in four valence states (-2, 0, +4, and +6) and

forms chemical compounds similar to those of sulfur. The heavy metal selenides (-2) are insoluble in water, as is elemental selenium. The inorganic alkali selenites (+4) and selenates (+6) are soluble in water (Weast 1988) and are therefore more bioavailable. Conditions such as pH (negative log hydrogen ion concentration), Eh (oxidation-reduction potential), and the presence of metal oxides affect the partitioning of the various compounds of selenium in the environment. In general, elemental selenium is stable in soils and is found at low levels in water because of its ability to coprecipitate with sediments. The soluble selenates are readily taken up by plants and converted to organic compounds such as selenomethionine, selenocysteine, dimethyl selenide, and dimethyl diselenide. Selenium is bioaccumulated by aquatic organisms and may also biomagnify in aquatic organisms.

3 EXPOSURE ASSESSMENT

This section addresses human and environmental exposure pathways as well as the potential human health and environmental impacts of the constituents of concern in groundwater attributable to Smith Ranch operations.

3.1 Human Exposure Potential from COCs at Point of Exposure

As shown in the conceptual model (Fig. 1), water from an impacted well is considered to be the only mechanism for an on-site resident to incur a potential adverse health effect from the Smith Ranch mine site. The primary complete pathway for human exposure is direct ingestion of groundwater at the point of exposure (POE). Indirect exposure pathways include consumption of vegetables irrigated with well water or meat from domestic animals or wild game that ingest water directly from the well or consume forage irrigated with the well water. Dermal exposure and inhalation exposure during bathing in well water also constitute complete pathways for intake of the COCs but are likely to be of minor importance compared to direct ingestion of groundwater or ingestion of locally-raised meat and vegetables.

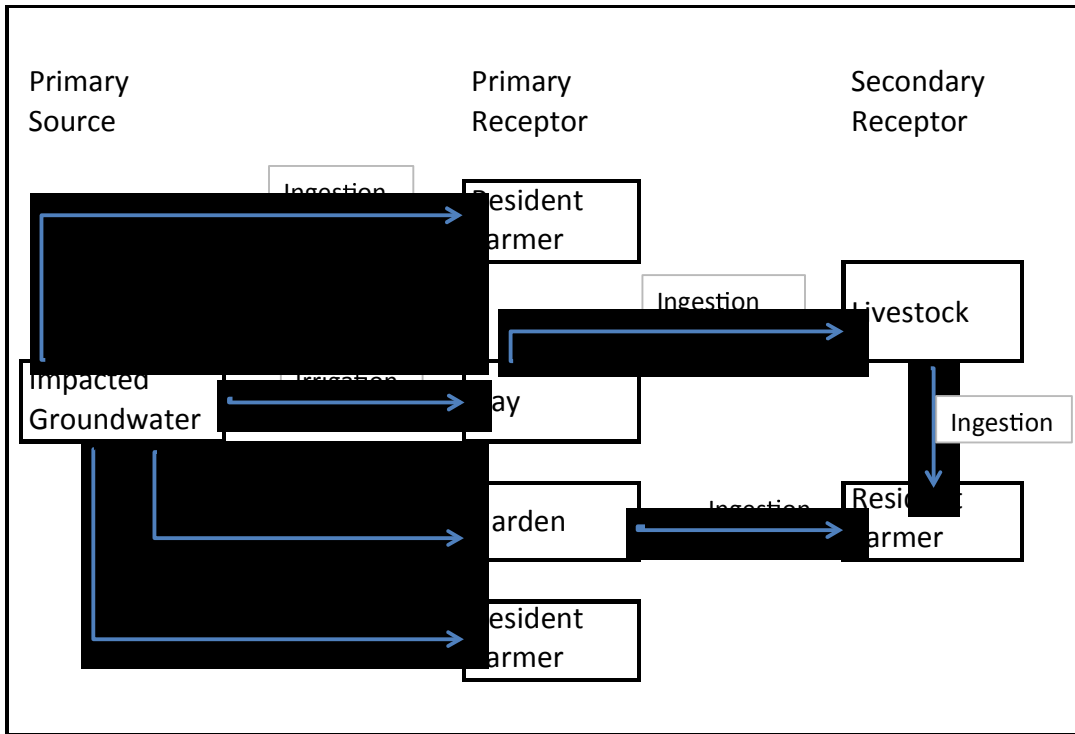


Figure 1 Conceptual model of risk from impacted groundwater.

3.1.1 Uranium

The potential radiation dose and risks to a resident farmer were calculated for a nominal uranium concentration using the following assumptions:

- All drinking, irrigation and bathing water comes from same potentially impacted well,
- The nominal uranium concentration is 1.0 Bq L^{-1} ($40 \text{ } \mu\text{g L}^{-1}$ assuming equilibrium),
- Cattle directly consume well water and forage irrigated with well water,
- The resident farmer consumes beef fed with irrigated forage
- The resident bathes in water from the well.

Radiation doses are calculated on an annual basis. Risks are estimated over a potential residence duration of 30 years. The potential dose and risk are calculated assuming a nominal U-nat concentration of 1.0 Bq L^{-1} (27 pCi L^{-1} ; $40 \text{ } \mu\text{g L}^{-1}$) in impacted groundwater. The dose and risk are directly proportional to the concentration; thus can be scaled up or down according to the groundwater concentration.

Unless otherwise noted, exposure parameter values are taken from NRC Report No. 123 (1996), Screening Models for Releases of Radionuclides to the Atmosphere, Surface water and Ground, and the EPA Exposure Factors Handbook (2011). Due to the long half-life of U-238, 4.5 billion years, calculations do not include decay corrections.

3.1.1.1 Carcinogenesis

3.1.1.1.1 Potential Radiation Dose and Risk from Drinking Impacted Groundwater

Drinking impacted groundwater is the primary exposure pathway and can result in potential radiation dose and increased risk of cancer to the resident farmer as well as toxicological effects. Doses and possible radiogenic risks are calculated below. Chemical toxicity is addressed in Section 3.1.1.2.

Estimated uranium intake to a resident from direct ingestion of groundwater is as follows:

$$\text{Uranium intake, } I_U = C_w * I_w * 365 \text{ d y}^{-1} = 1.0 \text{ Bq L}^{-1} * 1.23 \text{ L d}^{-1} * 365 \text{ d y}^{-1} = 449 \text{ Bq y}^{-1}$$

where $I_U =$ Resident uranium intake (Bq y^{-1})
 $C_w =$ Uranium concentration in well water (1 Bq L^{-1})
 $I_w =$ Resident intake of water (1.23 L d^{-1}) (EPA, 2011)

The dose coefficient (dose per unit intake) for uranium is $7.27\text{E-}8 \text{ Sv Bq}^{-1}$ (EPA, 1988). Therefore, the potential dose to resident is as follows:

$$D_w = I_U * \text{DCF} = 449 \text{ Bq y}^{-1} * 7.27 \text{ E-}8 \text{ Sv Bq}^{-1} * 1 \text{ E}5 \text{ mrem Sv}^{-1} = 3.3 \text{ mrem y}^{-1}$$

where $D_w =$ Dose from drinking well water (mrem/ yr)
 $I_U =$ Resident uranium intake (449 Bq y^{-1}) and
 $\text{DCF} =$ Dose conversion factor ($7.27 \text{ E-}8 \text{ Sv Bq}^{-1}$).

This dose attributable to drinking impacted groundwater at 1.0 Bq L^{-1} is approximately 1.2 percent of the dose the average American receives in a year from ubiquitous background radiation exposure as reported in NCRP Report No. 160 (2009).

Using risk coefficients from Federal Guidance Report No. 13 (EPA, 1998), the thirty-year lifetime mortality risk to a resident from drinking water would be as follows:

$$\text{Risk} = I_U * T * \text{RCF}_f = 449 \text{ Bq y}^{-1} * 30 \text{ y} * 1.19 \text{ E-}9 \text{ Bq}^{-1} = 1.6 \text{ E-}5$$

Where $I_U =$ Resident uranium intake (449 Bq y^{-1}),
 $\text{RCF}_f =$ Mortality risk coefficient factor, ($1.19 \text{ E-}9 \text{ Bq}^{-1}$) and
 $T =$ Duration of residence (30 y).

The value of $1.6\text{E-}5$ is well within the acceptable risk range of 10^{-6} to 10^{-4} .

The thirty-year morbidity risk to resident from drinking water would be as follows:

$$\text{Risk} = I_U * T * \text{RCF}_m = 449 \text{ Bq y}^{-1} * 30 \text{ y} * 1.82 \text{ E-}9 \text{ Bq}^{-1} = 2.5 \text{ E-}5$$

Where $I_U =$ Uranium intake (449 Bq y^{-1}),
 $\text{RCF}_m =$ Morbidity risk coefficient factor ($1.82 \text{ E-}9 \text{ Bq}^{-1}$) and
 $T =$ Length of consumption period (30 y).

The risks of mortality and morbidity are within the acceptable risk range at a groundwater concentration of 1.0 Bq L⁻¹. As noted above, the risks and doses, calculated based on a nominal uranium concentration of 1 Bq L⁻¹, can be scaled up or down linearly with concentration.

3.1.1.1.2 Buildup of Uranium in Soil

Irrigating with impacted water could lead to increased concentrations in the surface soil and uptake in both vegetables and forage. The average daily buildup of uranium in soil at a nominal groundwater uranium concentration of 1.0 Bq L⁻¹ can be calculated as follows using generic irrigation parameter values from NCRP 123 (1996):

$$I_s = [IR (L m^{-2} d^{-1}) * C_{GW} (Bq L^{-1}) * IP (d y^{-1})] / [MD (cm) * \rho (g cm^{-3}) * 365 d y^{-1} * 1E4 cm^2 m^{-2}] = 9.13 E-6 Bq g^{-1} d^{-1}$$

Where	$I_s =$	Intake to soil (Bq g ⁻¹)
	$IR =$	Rate of irrigation (5 L m ⁻² d ⁻¹),
	$MD =$	Soil mixing depth (15 cm),
	$IP =$	Irrigation period (150 d y ⁻¹),
	$\rho =$	Soil density (1.5 g cm ⁻³).

[Note: The consumptive irrigation requirement (CIR) for alfalfa grown in Douglas, Wyoming was reported to be 27.81 inches per season for a 186-day growing season (Pochop, 1992)]. When appropriate unit conversions are applied is approximately 700 L m⁻² for the growing season. The ICRP 123 volume of irrigation water assumed for this calculation is 5 L m⁻² d⁻¹ for a 150-day growing season or 750 L m⁻², a slightly more conservative value. The more conservative value is retained in these calculations to be consistent with other assumptions taken from NCRP 123 (1996). Pochop (1992) did not provide a CIR for garden vegetables.)

The uranium in soil will accumulate over time with each added year of irrigation. However, the uranium will also be removed from the soil by leaching and uptake in plants. The concentration in the soil will increase to an equilibrium level over time as follows:

$$C_{Seq} = I_s \lambda_s^{-1} = 9.13E-6 Bq g^{-1} d^{-1} / 2.70E-5 d^{-1} = 3.38E-01 Bq g^{-1}$$

Where	$C_{Seq} =$	Soil concentration at equilibrium (Bq g ⁻¹),
	$\lambda_s =$	Soil removal constant (leaching and uptake) [i.e., the fraction of uranium present that is removed per day] = 2.70E-5 d ⁻¹ (NCRP, 1999).

Over the course of the 30-yr duration of this analysis, the soil concentration will build up to:

$$C_s = C_{Seq} * (1 - e^{-\lambda t}) = 3.38E-01 Bq g^{-1} (1 - e^{-9.86E-3 * 30}) = 8.66E-2 Bq g^{-1},$$

This concentration will be used for subsequent calculations of dose and risk from eating irrigated vegetables and beef.

3.1.1.1.3 Potential Dose and Risk to Resident from Irrigated Vegetables

Plants grown in an irrigated garden would be subject to contamination from external deposition of sprayed water or from uptake of uranium from the soil. It is unlikely that sprayed vegetables would be eaten without washing; therefore, deposition of sprayed irrigation water or soil on the surface of the vegetables is not considered in this analysis. However, vegetables grown on the soil that has been irrigated over a period of 30 years could incorporate some uranium. The concentration of uranium in vegetables grown on irrigated soil is given by the equation

$$C_{veg} = C_{gw} * CF_{veg} = 8.66E-2 \text{ Bq g}^{-1} * 2E-3 * 1E3 \text{ g kg}^{-1} = 0.173 \text{ Bq/kg plant}$$

Where C_{veg} = concentration of uranium in vegetation (Bq kg^{-1} plant),
 C_S = concentration of uranium in soil ($8.7E-2 \text{ Bq g}^{-1}$),
 CF_{veg} = unitless concentration factor for uranium ($2E-3 \text{ Bq kg}^{-1}$ plant per Bq kg^{-1} soil) (NCRP, 1999).

This should be considered a maximum plant concentration because the 30-year concentration of uranium in the soil was used rather than an average value over that period.

EPA's Exposure Factor Handbook (EPA 2011) Table 9-3 lists vegetable consumption at $2.5 \text{ g kg}^{-1}\text{-d}^{-1}$ for a resident aged 20 to 49 years. For a 70 kg reference person, that would equate to 175 g d^{-1} or 63.9 kg y^{-1} of vegetable consumption. It is assumed that the residents would obtain 50% of their annual vegetable consumption from home-grown sources for a total consumption of 32 kg y^{-1} . The potential dose to a resident from eating irrigated vegetables containing uranium is shown below:

$$D_{veg} = 32 \text{ kg y}^{-1} * C_{veg} * DCF * 1 \text{ E5 mrem Sv}^{-1} = 4.04E-2 \text{ mrem y}^{-1},$$

Where D_{veg} = Dose from eating vegetables (mrem y^{-1})
 C_{veg} = Concentration in vegetables (0.174 Bq kg^{-1} plant), and
 DCF = Dose conversion factor ($7.27 \text{ E-8 Sv Bq}^{-1}$).

This dose is approximately 1% of the dose from drinking impacted well water.

The intake of uranium from eating vegetables is equivalent to $32 \text{ kg y}^{-1} * 0.173 \text{ Bq kg}^{-1} = 5.54 \text{ Bq y}^{-1}$. Using foodstuff risk coefficients from Federal Guidance Report No. 13 (EPA, 1998), the thirty-year lifetime mortality risk to a resident from eating vegetables irrigated with well water would be as follows::

$$\text{Risk} = I_{veg} * T * RCF_f = 5.54 \text{ Bq y}^{-1} * 30 \text{ y} * 1.59 \text{ E-9 Bq}^{-1} = 2.64E-7$$

Where I_{veg} = Resident uranium intake (5.54 Bq y^{-1}),
 RCF_f = Mortality risk coefficient factor, (1.59 E-9 Bq^{-1}) and
 T = Length of consumption period (30 y).

The value of $2.64E-7$ is well below the acceptable risk range of 10^{-6} to 10^{-4} .

Thirty-year lifetime morbidity risk to resident from eating vegetables may be calculated by:

$$\text{Risk} = I_U * T * RCF_m = 5.54 \text{ Bq y}^{-1} * 30 \text{ y} * 2.46 \text{ E-9 Bq}^{-1} = 4.09\text{E-7},$$

Where I_U = Uranium intake (5.54Bq y⁻¹),
 RCF_m = Morbidity risk coefficient factor (2.46E-9 Bq⁻¹) and
 T = Length of consumption period (30 y).

3.1.1.1.4 Potential Dose and Risk to Resident from Eating Beef

The concentration of uranium in beef from cattle drinking impacted water is given by the equation:

$$C_{\text{Beef}} = C_{\text{gw}} * Q_W * CF = 1.0 \text{ Bq L}^{-1} * 50 \text{ L d}^{-1} * 8 \text{ E-4 d kg}^{-1} = 4.0 \text{ E-2 Bq kg}^{-1},$$

Where C_{Beef} = Concentration of uranium in beef (Bq kg⁻¹ beef),
 C_{GW} = Concentration of uranium in well water (1 Bq L⁻¹),
 Q_{BW} = Quantity of water intake by cattle (50 L d⁻¹), and
 CF_{Beef} = Concentration factor for uranium in Bq kg⁻¹ beef per Bq d⁻¹ intake (8E-4 d kg⁻¹ beef).

To estimate the potential concentration of uranium in beef from eating forage grown on irrigated soil, the potential concentration of uranium in the forage itself must be calculated. As mentioned above in the discussion of mechanisms for contamination of vegetables, forage may be impacted by two mechanisms: uptake from soil and direct deposition from irrigation water. In this case, both must be considered because forage would be fed to cattle on an unwashed basis.

Uptake of uranium by forage from soil can be calculated using the following equation:

$$C_{\text{For-soil}} = C_S * CF_{\text{For}} = 8.66\text{E-2 Bq g}^{-1} * 0.1 \text{ Bq kg}^{-1} (\text{forage}) / \text{Bq kg}^{-1} (\text{soil}) * 1\text{E3 g kg}^{-1} = 8.66 \text{ Bq kg}^{-1},$$

Where $C_{\text{For-soil}}$ = Concentration in forage (Bq kg⁻¹),
 C_S = Concentration of uranium in soil (8.66E-2 Bq g⁻¹),
 F_{For} = Forage concentration factor (0.1 Bq kg⁻¹ plant per Bq kg⁻¹ soil).

A fraction of the irrigation water sprayed onto the forage crop, assumed to be alfalfa, will be retained as surface contamination. This interception fraction is assumed to be 1%. It is further assumed that the deposition from the previous irrigation event will be washed off the surface and there will be no build up from irrigation event to subsequent irrigation event. So, the period of irrigation is assumed to be a single day. According to WBC (2015), the average yield of irrigated alfalfa hay during the period 2005 to 2008 was 3.3 tons per acre (t/ac). (For more recent years, the notation of cropping practice was discontinued and only total alfalfa yield was indicated.)

Using those conditions, the concentration of uranium in forage from direct deposition by irrigation onto the surface of the plant may be calculated as follows:

$$C_{\text{For-irr}} = (C_{\text{GW}} * \text{IR} * \text{IP} * f) / Y = (1 \text{ Bq L}^{-1} * 5 \text{ L m}^{-2} \text{ d}^{-1} * 0.01 * 4.05\text{E}3 \text{ m}^2 \text{ ac}^{-1} * 1\text{E}3 \text{ g kg}^{-1}) / (3.3 \text{ ton ac}^{-1} * 9.08\text{E}5 \text{ g t}^{-1}) = 6.6\text{E}-2 \text{ Bq kg}^{-1} \text{ forage,}$$

Where $C_{\text{For-irr}}$ = Concentration in forage from direct deposition (Bq kg⁻¹ forage),
 IR = Irrigation rate (5 L m⁻²-day),
 IP = Irrigation period (1 d),
 f = interception fraction (0.01)
 Y = Crop yield (3.3 ton ac⁻¹).

The concentration of uranium in forage from soil uptake as well as direct deposition would be the sum of the two pathways for a total of 8.73 Bq kg⁻¹ forage.

It is unlikely that cattle will be fed alfalfa forage on a year round basis. It is far more likely that the alfalfa will be used only as a supplement to pasture grass. However, for ease of calculation, it is assumed that irrigated forage consumption would continue on a year round basis.

The concentration in beef from eating forage may be calculated as follows:

$$C_{\text{Beef}} = C_{\text{For}} * Q_{\text{For}} * C_{\text{F}_{\text{beef}}} = 8.73 \text{ Bq kg}^{-1} * 12 \text{ kg d}^{-1} * 8\text{E}-4 \text{ d kg}^{-1} = 8.38\text{E}-2 \text{ Bq kg}^{-1},$$

Where C_{Beef} = Concentration of uranium in beef (Bq kg⁻¹ beef),
 C_{For} = Concentration in forage (8.73 Bq kg⁻¹)
 Q_{For} = Quantity of forage intake by cattle (12 kg d⁻¹), and
 $C_{\text{F}_{\text{Beef}}}$ = Concentration factor for uranium (8E-4 d kg⁻¹ beef).

The total concentration of uranium in beef that results from livestock drinking well water and eating forage grown on soil irrigated with well water and from direct deposition of irrigation water on the forage is 0.124 Bq kg⁻¹ of meat.

EPA's Exposure Factor Handbook (EPA 2011) Table 11-4 lists meat consumption for a 20 to 49-year old to be 1.8 g kg⁻¹ d⁻¹ for the edible, uncooked portion. For a 70 kg reference person, that would equate to 126 g/day or 46 kg/yr of meat consumption. The potential dose to a resident from eating beef containing uranium is shown below:

$$D_{\text{Beef}} = I_{\text{Beef}} * C_{\text{Beef}} * \text{DCF} = 46 \text{ kg y}^{-1} * 1.24\text{E}-1 \text{ Bq kg}^{-1} * 7.27\text{E}-8 \text{ Sv Bq}^{-1} = 4.15\text{E}-7 \text{ Sv y}^{-1} = 4.15\text{E}-2 \text{ mrem y}^{-1},$$

Where D_{Beef} = Dose to resident from eating home grown beef (mrem y⁻¹)
 I_{Beef} = annual consumption of beef (46 kg y⁻¹),
 C_{Beef} = uranium concentration in beef (0.124 Bq kg⁻¹), and
 DCF = 7.27 E-8 Sv Bq⁻¹.

The intake of uranium from eating beef is equivalent to the annual consumption of beef, 46 kg y⁻¹, multiplied by the uranium concentration in beef, 0.124 Bq kg⁻¹, for a total of 5.69 Bq y⁻¹. Using foodstuff risk coefficients from Federal Guidance Report No. 13 (EPA, 1998), the thirty-year lifetime mortality risk to a resident from eating beef may be calculated by:

$$\text{Risk} = I_{\text{Beef}} * T * \text{RCF}_f = 5.69 \text{ Bq y}^{-1} * 30 \text{ y} * 1.59 \text{ E-9 Bq}^{-1} = 2.72\text{E-7}$$

Where I_{Beef} = Resident uranium intake (5.69 Bq y⁻¹),
 RCF_f = Mortality risk coefficient factor, (1.59 E-9 Bq⁻¹) and
 T = Length of consumption period (30 y).

The value of 2.72E-7 is below the acceptable risk range of 10⁻⁶ to 10⁻⁴.

Thirty-year lifetime morbidity risk to resident from eating beef may be calculated by:

$$\text{Risk} = I_U * T * \text{RCF}_m = 5.69 \text{ Bq y}^{-1} * 30 \text{ y} * 2.46\text{E-9 Bq}^{-1} = 4.20\text{E-7}$$

Where I_U = Uranium intake (5.69 Bq y⁻¹),
 RCF_m = Morbidity risk coefficient factor (2.46 E-9 Bq⁻¹) and
 T = Length of consumption period (30 y).

3.1.1.1.5 Potential Risk from Bathing

As reported in ATSDR (2013) there have been no deaths in humans as a result of dermal exposure to uranium. Animal experiments have been conducted to determine sensitivity to dermal exposure in several animal species. Some deaths have occurred in animals after dermal exposure to uranium compounds from both single and repeated exposures. The more water-soluble uranium compounds were the most toxic and the rabbit was the most sensitive species. Deaths were due to renal failure.

Because uranium is not easily absorbed through the skin, carcinogenesis from that pathway is considered to be unlikely.

3.1.1.1.6 Summary of Uranium Radiation Effects

Table 1 is a summary of the calculated dose and risk estimates from intake of uranium contained in well water, assuming 1.0 Bq/L of water. Dose and risk are dominated by the drinking water pathway. The impact from eating vegetables and beef that resulted from irrigating with well water is only about 2.5% of that from drinking well water.

Table 1 Summary of doses and risks calculated from use of impacted well water for unit concentration of uranium.

Exposure Pathway	Calculated Dose (mrem y ⁻¹)	30-year Risk Estimate	
		Mortality	Morbidity
Drinking water	3.26E+00	1.60E-05	2.45E-05
Eating vegetables	4.03E-02	2.64E-07	4.09E-07
Eating beef	4.14E-02	2.72E-07	4.20E-07
Bathing	N/A	N/A	N/A
Total	3.35E+00	1.64E-05	2.51E-05

3.1.1.2 Systemic Toxicity of Uranium

Uranium is chemically toxic to the kidneys in addition to being radioactive. The chemical toxicity is the limiting factor for soluble uranium. The hazard quotient is the ratio of the average daily intake to a reference dose (RfD) derived from animal or human toxicity studies. In general, the reference dose is based on the lowest observed adverse effect level (LOAEL) or the no observed adverse effect level (NOAEL). A safety factor is applied to account for the uncertainty in the studies used and depends on whether the NOAEL or LOAEL is based on human or animal data. The safety factor can range from 10 to 1,000 depending on the quality of the data. The oral RfD for soluble uranium is $0.0002 \text{ mg kg}^{-1} \text{ d}^{-1}$ (EPA, 2017)

Assuming the total ingestion of uranium by the resident farmer from direct water ingestion and ingestion of vegetables or beef raised using groundwater for irrigation, the total daily ingestion rate for the nominal groundwater concentration of 1.0 Bq L^{-1} (0.040 mg L^{-1}) would be as follows:

$$\text{Direct water ingestion} = 0.040 \text{ mg L}^{-1} * 1.23 \text{ L/d} = 4.9 \text{ E-2 mg d}^{-1}$$

$$\text{Beef ingestion} = (0.124 \text{ Bq kg}^{-1} * 0.040 \text{ mg Bq}^{-1} * 46 \text{ kg y}^{-1})/365 \text{ d y}^{-1} = 6.25 \text{ E-4 mg d}^{-1}$$

$$\text{Vegetable ingestion} = (0.173 \text{ Bq kg}^{-1} * 32 \text{ kg y}^{-1} * 0.040 \text{ mg Bq}^{-1})/365 \text{ d y}^{-1} \\ = 6.1 \text{ E-4 mg d}^{-1}$$

Total daily ingestion of uranium = 0.050 mg d^{-1} . Assuming a 70 kg adult, the dose in $\text{mg kg}^{-1} \text{ d}^{-1}$ would be as follows

$$\text{Dose} = 0.050 \text{ mg d}^{-1}/70 \text{ kg} = 0.00071 \text{ mg kg}^{-1} \text{ d}^{-1}$$

The Hazard Quotient (HQ) is the daily dose divided by the reference dose. In this case, the HQ is $0.00071 \text{ mg kg}^{-1} \text{ d}^{-1}/0.0002 \text{ mg kg}^{-1} \text{ d}^{-1} = 3.6$.

A HQ greater than 1.0 does not necessarily indicate a toxic level; however, a HQ less than 1.0 generally indicates a safe daily intake. The RfD includes a safety factor ranging from 10 to 1,000. In 2017, the EPA reduced the RfD for soluble uranium from 0.003 to 0.0002 (EPA, 2017) based on a re-assessment of the animal toxicity data.

Approximately 98% of the intake comes from direct ingestion of ground water. The water was not potable before the Smith Ranch ISR operations commenced.

According to ATSDR (2013), no studies were found regarding systemic effects in humans following either acute, intermediate, or chronic duration dermal exposure to uranium. Further, there were no studies found regarding the respiratory, cardiovascular, gastrointestinal, hematological, hepatic, or endocrine effects of uranium in animals for any duration of exposure.

3.1.1.3 Derived Concentration Guideline Level (DCGL) for Uranium

The DCGL is a radionuclide-specific surface or volume residual radioactivity level that is related to a concentration, dose or risk criterion. A reasonable dose criterion for establishing a DCGL for uranium in groundwater attributable to Mine Unit 1 operations is 25 mrem y⁻¹. Based on the annual radiation dose calculated for a resident farmer using a nominal uranium concentration in groundwater of 0.040 mg L⁻¹, 3.35 mrem y⁻¹, the DCGL would be as follows:

$$\text{DCGL} = C_{\text{gw}} * \text{Dose criterion} / \text{Calculated dose}$$

$$\text{DCGL} = 0.040 \text{ mg L}^{-1} * 25 \text{ mrem y}^{-1} / 3.35 \text{ mrem y}^{-1} = 0.30 \text{ mg L}^{-1} \text{ or } 7.5 \text{ Bq L}^{-1}$$

While not strictly applicable, a comparable DCGL can be derived for uranium in groundwater based on the calculated HQ of 3.4.

$$\text{DCGL} = 0.040 \text{ mg L}^{-1} * 1.0 / 3.4 = 0.012 \text{ mg L}^{-1}$$

It should be noted that this DCGL is a factor of 2.5 lower than the drinking water standard of 0.030 mg L⁻¹. The most recent EPA Regional Screening Level RfD was used in the HQ calculation. The RfD was decreased from 0.003 to 0.0002 in 2017 (EPA, 2017). A DCGL of 0.030 mg L⁻¹ is appropriate for the Mine Unit 1 groundwater.

These DCGLs apply only to the point of exposure. They do not apply to the point of compliance.

3.1.1.4 Dose and Risk from Uranium Concentration in Groundwater at the POE

The maximum modeled uranium concentration in groundwater within 1,000 years at the POE is 8.05E-06 mg L⁻¹. The potential dose to a resident farmer at the maximum uranium concentration would be directly proportional to the dose and risk calculated for the nominal concentration, 0.040 mg L⁻¹. The calculated dose and risks at the POE are shown in Table 2.

The potential doses and risks at the POE at the maximum modeled uranium concentration are negligible.

Table 2 Dose and risk at the POE at the maximum modeled uranium concentration.

Exposure Pathway	Calculated Dose (mrem)		30 year Risk Estimate (mortality)		30-year Risk Estimate (morbidity)	
	Nominal	Predicted POE	Nominal	Predicted POE	Nominal	Predicted POE
Drinking water	3.3 E+00	6.6 E-04	1.6 E-05	3.2 E-09	2.5 E-05	5.0 E-09
Eating Vegetables	4.0 E-02	8.1 E-06	2.6 E-07	5.3 1E-11	4.1 E-07	8.2 E-11
Eating Beef	4.1 E-02	8.3 E-06	2.7 E-07	5.5 E-11	4.2 E-07	8.5 E-11
Total	3.4E+00	6.8 E-04	1.7 E-05	3.3 E-09	2.6 E-05	5.2 E-09

3.1.2 Arsenic

For consideration of potential effects from arsenic in the well water, the assumptions for are similar to those used when considering uranium:

- All drinking, irrigation and bathing water comes from same potentially impacted well,
- The nominal arsenic concentration is $1.0 \text{ E-3 mg L}^{-1}$
- Cattle directly consume well water and forage irrigated with well water,
- The resident farmer consumes beef fed with irrigated forage
- The resident bathes in water from the well.

The adverse health effects of exposure to arsenic include increased risk of skin cancer and systemic toxicity.

3.1.2.1 Carcinogenesis

Carcinogenic risks are estimated for a residence duration of 30 years. The risk is directly proportional to the concentration and may be adjusted according to the concentration of arsenic in the well water. Unless otherwise noted, exposure parameters are taken from NRCF Report No. 123 (1986) and the EPA Exposure Factors Handbook (2011).

With few exceptions, the equations used to calculate concentrations in foodstuffs and intakes are the same for arsenic as uranium. Differences include the use of a slope factor to calculate carcinogenic risk rather than a dose conversion factor and subsequent risk factors for radiogenic risk.

3.1.2.1.1 Potential Risk from Drinking Impacted Groundwater

Drinking impacted groundwater is the primary exposure pathway and can result in increased risk of cancer to the resident farmer.

Arsenic intake to resident from direct ingestion of groundwater is as follows:

$$\text{Intake, } I_{As} = C_w * I_w * 365 \text{ d y}^{-1} = 1\text{E-3 mg L}^{-1} * 1.23 \text{ L d}^{-1} * 365 \text{ d y}^{-1} = 0.45 \text{ mg y}^{-1}$$

where

I_{As}	=	Resident arsenic intake (mg y^{-1})
C_w	=	Arsenic concentration in well water ($1.0 \text{ E-3 mg L}^{-1}$)
I_w	=	Resident intake of water (EPA, 2011)

Potential development of skin cancer is the main risk from chronic intake of arsenic in water. EPA (1987) has reported an oral cancer slope factor of 1.5 kg d mg^{-1} for inorganic arsenic based on human dose-response data. So, the risk may be calculated as:

$$\text{Risk} = (C_A * I_W * EF * T * SF) / (BW * AT) = 2.6E-5,$$

Where

C_{As}	=	Concentration of As in water (1.0 E-3 mg L ⁻¹),
I_W	=	Water intake (1.23 L day ⁻¹),
EF	=	Exposure frequency (365 day yr ⁻¹),
T	=	Exposure duration (30 yr),
SF	=	Slope factor (1.5 [mg/kg-day] ⁻¹),
BW	=	Body weight (70 kg), and
AT	=	Average exposure days (30 yr * 365 day yr ⁻¹).

The value of 2.6E-5 is well within the acceptable risk range of 10⁻⁶ to 10⁻⁴.

3.1.2.1.2 Buildup of Arsenic in Soil

Irrigating with impacted water could lead to increased concentrations in the surface soil and uptake in both vegetables and forage. The average daily increase in arsenic concentration in soil at a nominal groundwater concentration of 1.0E-3 mg L⁻¹ can be calculated as follows:

$$I_S = (IR * C_{GW} * IP) / (MD * \rho * 365 \text{ d yr}^{-1} * 1 \text{ E4 cm}^2 \text{ m}^{-2}) = 9.13 \text{ E-9 mg g}^{-1}$$

Where

I_S	=	Intake to soil (mg g ⁻¹)
C_{GW}	=	Arsenic concentration in water (1.0 E-3 mg L ⁻¹)
IR	=	Rate of irrigation (5 L m ⁻² d ⁻¹),
MD	=	Soil mixing depth (15 cm),
IP	=	Irrigation period (150 d yr ⁻¹),
ρ	=	Soil density (1.5 g cm ⁻³).

The arsenic in soil will accumulate over time with each added year of irrigation. However, the arsenic will also be removed from the soil by leaching and uptake in plants. The concentration in the soil will increase to an equilibrium level over time as follows:

$$C_{Seq} = I_S \lambda_S^{-1} = 9.13 \text{ E-9 mg g}^{-1} \text{ d}^{-1} / 2.70 \text{ E-5 d}^{-1} = 3.38 \text{ E-4 mg g}^{-1}$$

Where

C_{Seq}	=	Soil concentration at equilibrium (Bq g ⁻¹),
λ_S	=	Soil removal constant (leaching and uptake) = 2.70E-5 d ⁻¹ (NCRP, 1999).

Over the course of the 30-yr duration of this analysis, the soil concentration will build up to:

$$C_S = C_{Seq} * (1 - e^{-\lambda t}) = 3.38 \text{ E-04 mg g}^{-1} (1 - e^{-9.86E-3 * 30}) = 8.66 \text{ E-5 mg g}^{-1},$$

This concentration will be used for subsequent calculations risk from eating irrigated vegetables and beef.

3.1.2.1.3 Potential Risk to Resident from Irrigated Vegetables

Plants grown in an irrigated garden would be subject to contamination from external deposition of sprayed water or from uptake of arsenic from the soil. It is unlikely that sprayed vegetables would be eaten without washing; therefore, deposition of sprayed irrigation water or soil on the surface of the vegetables is not considered in this analysis. However, vegetables grown on the soil that has been irrigated over a period of 30 years would incorporate some arsenic. The concentration of arsenic in vegetables grown on irrigated soil is given by the equation:

$$C_{veg} = C_{gw} * CF_{veg} = 8.66E-5 \text{ mg g}^{-1} * 8 E-2 * 1 E3 \text{ g kg}^{-1} = 6.93 E-3 \text{ mg kg}^{-1} \text{ plant}$$

Where C_{veg} = concentration of As in vegetation (mg kg^{-1} plant),
 C_S = concentration of As in soil ($8.66\text{-}5 \text{ mg g}^{-1}$),
 CF_{veg} = unitless concentration factor for AS (0.08 mg kg^{-1} plant per mg kg^{-1} soil) (NCRP, 1999).

This should be considered a maximum plant concentration because the 30-year concentration of uranium in the soil was used rather than an average value over that period.

The Exposure Factors Handbook (EPA 2011) Table 9-3 lists vegetable consumption at $2.5 \text{ g kg}^{-1}\text{-d}^{-1}$ for a resident aged 20 to 49. For a 70 kg reference person, that would equate to 175 g d^{-1} or 63.9 kg y^{-1} of vegetable consumption. It is assumed that the resident would obtain 50% of their annual vegetable consumption from home-grown sources for a total consumption of 32 kg y^{-1} .

As above, using the slope factor listed in EPA (1987), the thirty-year risk to a resident from eating vegetables irrigated with well water would be as follows:

$$\text{Risk} = (C_A * I_V * T * SF) / (BW * AT) = 1.30 E-5$$

Where C_{veg} = Concentration of As in vegetables ($6.93 E-3 \text{ mg kg}^{-1}$ plant),
 I_V = Vegetable intake (32 kg yr^{-1}),
 T = Exposure duration (30 yr),
 SF = Slope factor ($1.5 [\text{ mg/kg-day}]^{-1}$),
 BW = Body weight (70 kg), and
 AT = Average exposure days ($30 \text{ yr} * 365 \text{ day yr}^{-1}$).

3.1.2.1.4 Potential Risk to Resident from Eating Beef

The concentration of arsenic in beef from cattle drinking impacted water is given by the equation:

$$C_{Beef} = C_{gw} * Q_W * CF = 1.0 E-3 \text{ mg L}^{-1} * 50 \text{ L d}^{-1} * 2 E-2 \text{ d kg}^{-1} = 1 E-3 \text{ mg kg}^{-1},$$

Where C_{Beef} = Concentration of arsenic in beef (mg kg^{-1} beef),
 C_{GW} = Concentration of arsenic in well water ($1E-3 \text{ mg L}^{-1}$),
 Q_{BW} = Quantity of water intake by cattle (50 L d^{-1}), and
 CF_{Beef} = Concentration factor for arsenic in mg kg^{-1} beef per mg d^{-1} intake ($2E-2 \text{ kg}^{-1}$ beef).

To estimate the potential concentration of arsenic in beef from eating forage grown on irrigated soil, the potential concentration of arsenic in the forage itself must be calculated. As mentioned above in the discussion of mechanisms for contamination of vegetables, forage may be impacted by two mechanisms: uptake from soil and direct deposition from irrigation water. In this case, both must be considered because forage would be fed to cattle on an unwashed basis.

Uptake of arsenic by forage from soil can be calculated using the following equation:

$$C_{\text{For-soil}} = C_S * C_{F_{\text{For}}} = 8.66\text{E-}5 \text{ mg g}^{-1} * 0.2 * 1\text{E}3 \text{ g kg}^{-1} = 1.73\text{E-}2 \text{ mg kg}^{-1},$$

Where $C_{\text{For-soil}}$ = Concentration in forage (mg kg^{-1}),
 C_S = Concentration of arsenic in soil ($8.66\text{E-}5 \text{ mg g}^{-1}$),
 F_{For} = Forage concentration factor (0.2 mg kg^{-1} plant per mg kg^{-1} soil).

A fraction of the arsenic in irrigation water sprayed onto the forage crop, assumed to be alfalfa, will be retained as surface contamination. This interception fraction is assumed to be 1%. It is further assumed that the deposition from the previous irrigation event will be washed off the surface and there will be no build-up of arsenic from an irrigation event to subsequent irrigation events. So, the period of irrigation is assumed to be a single day. According to WBC (2015), the average yield of irrigated alfalfa hay during the period 2005 to 2008 was 3.38 tons per acre (t ac^{-1}). (For more recent years, the notation of cropping practice was discontinued and only total alfalfa yield was indicated.)

Using those conditions, the concentration of arsenic in forage from direct deposition by irrigation onto the surface of the plant may be calculated as follows:

$$C_{\text{For-irr}} = (C_{\text{GW}} * \text{IR} * \text{IP} * f) / Y = (1.0 \text{ E-}3 \text{ mg L}^{-1} * 5 \text{ L m}^{-2} \text{ d}^{-1} * 0.01 * 4.05\text{E}3 \text{ m}^2 \text{ ac}^{-1} * 1\text{E}3 \text{ g kg}^{-1}) / (3.3 \text{ ton ac}^{-1} * 9.08\text{E}5 \text{ g t}^{-1}) = 6.6\text{E-}5 \text{ mg kg}^{-1} \text{ forage},$$

Where $C_{\text{For-irr}}$ = Concentration in forage from direct deposition (mg kg^{-1} forage),
 IR = Irrigation rate ($5 \text{ L m}^{-2}\text{-day}$),
 IP = Irrigation period (1 d),
 f = interception fraction (0.01)
 Y = Crop yield (3.38 ton ac^{-1}).

The concentration of arsenic in forage from soil uptake as well as direct deposition is the sum of the two pathways for a total of $1.74\text{E-}2 \text{ mg kg}^{-1}$ forage.

It is unlikely that cattle will be fed alfalfa forage on a year-round basis. It is far more likely that the alfalfa will be used only as a supplement to pasture grass. However, for ease of calculation, it is assumed that irrigated forage consumption would continue on a year-round basis.

The concentration in beef from eating forage may be calculated as follows:

$$C_{\text{Beef}} = C_{\text{For}} * Q_{\text{For}} * C_{F_{\text{beef}}} = 1.74 \text{ E-}2 \text{ mg kg}^{-1} * 12 \text{ kg d}^{-1} * 2\text{E-}2 \text{ d kg}^{-1} = 4.18 \text{ E-}3 \text{ mg kg}^{-1},$$

Where C_{Beef} = Concentration of arsenic in beef (mg kg^{-1} beef),
 C_{For} = Concentration in forage ($1.74\text{E-}2 \text{ mg kg}^{-1}$)

Q_{For} = Quantity of forage intake by cattle (12 kg d⁻¹), and
 CF_{Beef} = Concentration factor for arsenic (2E-2 d kg⁻¹ beef).

The total concentration of arsenic in beef that results from livestock drinking well water and eating forage grown on soil irrigated with well water and from direct deposition of irrigation water on the forage is 5.17 E-3 mg kg⁻¹ of meat.

EPA's Exposure Factors Handbook (EPA 2011) Table 11-4 lists meat consumption for a 20 to 49 year old to be 1.8 g kg⁻¹ d⁻¹ for the edible, uncooked portion. For a 70 kg reference person, that would equate to 126 g/day or 46 kg/yr of meat consumption.

$$\text{Risk} = (C_A * I_{Beef} * T * SF) / (BW * AT) = 1.40 \text{ E-5}$$

Where C_{veg} = Concentration of As in beef (5.17 E-3 mg kg⁻¹ beef),
 I_{Beef} = Beef intake (46 kg yr⁻¹),
 T = Exposure duration (30 yr),
 SF = Slope factor (1.5 [mg/kg-day]⁻¹),
 BW = Body weight (70 kg), and
 AT = Average exposure days (30 yr * 365 day yr⁻¹).

3.1.2.2 Systemic Toxicity of Arsenic

Ingestion of inorganic arsenic can cause systemic health effects including irritation of the gastrointestinal system, decreased production of red and white blood cells, fatigue, abnormal heart rhythm, blood-vessel damage and impaired nerve function. Chronic ingestion of arsenic can cause skin changes, including darkened skin and corns or warts. As addressed above, ingestion of arsenic can cause cancer (ATSDR, 2007). As with the uranium toxicity analysis, the Hazard Quotient (HQ) was calculated based on the total daily intake of arsenic, including direct ingestion of water, ingestion of irrigated vegetables, and ingestion of beef consuming well water and forage irrigated with well water.

Using the same assumptions and calculations for intake of arsenic as were employed in the cancer risk analysis above, the estimated daily intake of arsenic from all three pathways would be as follows:

$$I_{As} = C [(CR * EF * ED) / (BW * AT)]$$

Where: C = concentration in beef or vegetables from section 3.1.2 above:

C_{water} = 0.001 mg L⁻¹
 C_{beef} = 5.17E-3 mg kg⁻¹
 C_{veg} = 6.93E-3 mg kg⁻¹
 CR_{water} = contact rate = 1.23 L d⁻¹ for adult (EPA, 2011)
 CR_{beef} = contact rate = 1.8 E-3 kg d⁻¹ per kg body wt. (EPA, 2011)
 = 0.126 kg d⁻¹ for a 70 kg adult
 CR_{veg} = contact rate = 2.5 E-3 kg d⁻¹ per kg body wt. (EPA, 2011)
 = 0.175 kg d⁻¹ for a 70 kg adult
 EF = exposure frequency = 350 d y⁻¹

ED = exposure duration = 30 y
 BW = body weight in kg = 70 kg
 AT = averaging time (for non-carcinogens, the AT = ED x 365 d y⁻¹)

$$I_{\text{water}} = 1.0 \text{ E-3 mg L}^{-1} (1.23 \text{ L d}^{-1} * 350 \text{ d y}^{-1} * 30 \text{ y}) / (70 \text{ kg} * 30 \text{ y} * 365 \text{ d y}^{-1}) = 1.68\text{E-5 mg kg}^{-1} \text{ d}^{-1}$$

$$I_{\text{beef}} = 5.17 \text{ E-3 mg kg}^{-1} (0.126 \text{ kg d}^{-1} * 350 \text{ d y}^{-1} * 30 \text{ y}) / (70 \text{ kg} * 30 \text{ y} * 365 \text{ d y}^{-1}) = 8.92 \text{ E-6 mg kg}^{-1} \text{ d}^{-1}$$

$$I_{\text{veg}} = 6.93\text{E-3 mg kg}^{-1} (0.175 \text{ kg d}^{-1} * 350 \text{ d y}^{-1} * 30 \text{ y}) / (70 \text{ kg} * 30 \text{ y} * 365 \text{ d y}^{-1}) = 1.66 \text{ E-5 mg kg}^{-1} \text{ d}^{-1}$$

$$\text{Average daily intake, } I_{\text{As}} = I_{\text{water}} + I_{\text{beef}} + I_{\text{veg}} = (1.68\text{E-5} + 8.9 \text{ E-6} + 1.66 \text{ E-5}) \text{ mg kg}^{-1} \text{ d}^{-1} = 4.27 \text{ E-5 mg kg}^{-1} \text{ d}^{-1}.$$

The Hazard Quotient (HQ) is the average daily intake (I_{As}) divided by the reference dose. The reference dose for arsenic is 0.0003 mg kg⁻¹ d⁻¹. (EPA, 2017).

$$HQ_{\text{As}} = 4.27 \text{ mg kg}^{-1} \text{ d}^{-1} / 3.0 \text{ E-4 mg kg}^{-1} \text{ d}^{-1} = 0.14$$

As mentioned above in section 3.2.1, a HQ greater than 1.0 does not necessarily indicate a toxic level; however, a HQ less than 1.0 generally indicates a safe daily intake. The RfD includes a safety factor ranging from 10 to 1,000.

Dermal absorption of arsenic is considered a minor route of intake and is highly dependent on speciation. Therefore, it is not considered in this analysis.

The HQ is directly proportional to the concentration of arsenic in the groundwater. Therefore, the maximum potential concentration of arsenic resulting in a HQ equal to or less than 1.0 would be as follows:

$$C_{\text{As}} (\text{HQ} = 1.0) = 0.001 \text{ mg L}^{-1} / 0.057 = 0.018 \text{ mg L}^{-1}$$

This value is comparable to a DCGL as described above.

3.1.2.3 Risk from Arsenic Concentration in Groundwater at the POE

The maximum modeled future arsenic concentration in groundwater at the POE is 0.00 mg L⁻¹ (Enchemica, 2017). Therefore, no risk calculation was performed for the POE.

3.1.2.4

3.1.3 Potential Risk from Ra-226 at the Point of Exposure

Although Ra-226 (radium) is not to be included in the ACL petition, it is a useful exercise to estimate the potential effects from radium exposure using the same scenario as for uranium exposure.

All assumptions for this calculation are the same as above for uranium for the resident farmer scenario as follows:

- All drinking, irrigation and bathing water comes from same potentially impacted well,
- The nominal radium concentration is 1.0 Bq L⁻¹
- Cattle directly consume well water and forage irrigated with well water,
- The resident farmer consumes beef fed with irrigated forage
- The resident bathes in water from the well.

Radiation doses are calculated on an annual basis. Risks are estimated over a potential residence duration of 30 years. The potential dose and risk are calculated assuming a nominal Ra-226 concentration of 1.0 Bq L⁻¹ in impacted groundwater. The dose and risk are directly proportional to the concentration; thus can be scaled up or down according to the concentration.

3.1.3.1 Potential Radiation Dose and Risk from Drinking Impacted Groundwater

Drinking impacted groundwater is the primary exposure pathway and can result in potential radiation dose and increased risk of cancer to the resident farmer as well as toxicological effects. Doses and possible radiogenic risks are calculated below. (Note: The chemical toxicity of radium is not a factor compared to the radiotoxicity.)

Ra-226 intake to resident from direct ingestion of groundwater is as follows:

$$\text{Ra-226 intake, } I_U = C_w * I_w * 365 \text{ d y}^{-1} = 1.0 \text{ Bq L}^{-1} * 1.23 \text{ L d}^{-1} * 365 \text{ d y}^{-1} = 449 \text{ Bq y}^{-1}$$

where

I_U =	Resident Ra-226 intake (Bq y ⁻¹)
C_w =	Ra-226 concentration in well water (1.0 Bq L ⁻¹)
I_w =	Resident intake of water (1.23 L d ⁻¹) (EPA, 2011)

The dose coefficient (dose per unit intake) for radium is 3.58E-7 Sv Bq⁻¹ (EPA, 1988). Therefore, the potential dose to resident is as follows:

$$D_w = I_U * DCF = 449 \text{ Bq y}^{-1} * 3.58\text{E-}7 \text{ Sv Bq}^{-1} = 1.61\text{E-}4 \text{ Sv y}^{-1} = 16.1 \text{ mrem y}^{-1}$$

where

D_w =	Dose from drinking well water (mrem/ yr)
I_U =	Resident Ra-226 intake (449 Bq y ⁻¹) and
DCF =	Dose conversion factor (3.58E-7 Sv Bq ⁻¹).

Using risk coefficients from Federal Guidance Report No. 13 (EPA, 1998), the thirty-year lifetime mortality risk to a resident from Ra-226 in drinking water would be as follows::

$$\text{Risk} = I_U * T * RCF_f = 449 \text{ Bq y}^{-1} * 30 \text{ y} * 7.17 \text{ E-}9 \text{ Bq}^{-1} = 9.66\text{E-}5 \text{ yr}^{-1}$$

Where

I_U =	Resident Ra-226 intake (449 Bq y ⁻¹),
RCF_f =	Mortality risk coefficient factor (7.17E-9 Bq ⁻¹) and
T =	Duration of residence (30 y).

The value of 9.66E-5 is within the acceptable risk range of 10⁻⁶ to 10⁻⁴.

The thirty-year morbidity risk to a resident from drinking water would be as follows:

$$\text{Risk} = I_U * T * RCF_m = 449 \text{ Bq y}^{-1} * 30 \text{ y} * 1.04\text{E-}8 \text{ Bq}^{-1} = 1.40\text{E-}5$$

Where $I_U =$ Ra-226 intake (449 Bq y⁻¹),
 $RCF_m =$ Morbidity risk coefficient factor (1.04E-8 Bq⁻¹) and
 $T =$ Length of consumption period (30 y).

The risks of mortality and morbidity are within the acceptable risk range at a groundwater concentration of 1.0 Bq L⁻¹. As noted above, the risks and doses, calculated based on a nominal Ra-226 concentration of 1.0 Bq L⁻¹, can be scaled up or down linearly with concentration.

3.1.3.2 Buildup of Radium in Soil

Irrigating with impacted water could lead to increased concentrations in the surface soil and uptake in both vegetables and forage. The average daily increase in Ra-226 concentration in soil after one year of irrigation at a nominal groundwater Ra-226 concentration of 1.0 Bq L⁻¹ can be calculated as follows:

$$I_S = [IR (\text{L m}^{-2} \text{ d}^{-1}) * C_{GW} (\text{Bq L}^{-1}) * IP (\text{d y}^{-1})] / [MD (\text{cm}) * \rho (\text{g cm}^{-3}) * 365 \text{ d y}^{-1} * 1\text{E}4 \text{ cm}^2 \text{ m}^{-2}] = 9.13 \text{ E-}6 \text{ Bq g}^{-1} \text{ d}^{-1}$$

Where $I_S =$ Intake to soil (Bq g⁻¹)
 $IR =$ Rate of irrigation (5 L m⁻² d⁻¹),
 $MD =$ Soil mixing depth (15 cm),
 $IP =$ Irrigation period (150 d y⁻¹),
 $\rho =$ Soil density (1.5 g cm⁻³).

The Ra-226 in soil will accumulate over time with each added year of irrigation. However, the Ra-226 will also be removed from the soil by leaching and uptake in plants. The concentration in the soil will increase to an equilibrium level over time as follows:

$$C_{Seq} = I_S \lambda_S^{-1} = 9.13\text{E-}6 \text{ Bq g}^{-1} \text{ d}^{-1} / 2.70\text{E-}5 \text{ d}^{-1} = 3.38\text{E-}01 \text{ Bq g}^{-1}$$

Where $C_{Seq} =$ Soil concentration at equilibrium (Bq g⁻¹),
 $\lambda_S =$ Soil removal constant (leaching and uptake) = 2.70E-5 d⁻¹ (NCRP, 1999).

Over the course of the 30-yr duration of this analysis, the soil concentration will build up to:

$$C_S = C_{Seq} * (1 - e^{-\lambda t}) = 3.38\text{E-}01 \text{ Bq g}^{-1} (1 - e^{-9.86\text{E-}3 * 30}) = 8.66\text{E-}2 \text{ Bq g}^{-1},$$

This concentration will be used for subsequent calculations of dose and risk from eating irrigated vegetables and beef.

3.1.3.3 Potential Dose and Risk to Resident from Irrigated Vegetables

Plants grown in an irrigated garden would be subject to contamination from external deposition of sprayed water or from uptake of Ra-226 from the soil. It is unlikely that sprayed vegetables would be eaten without washing; therefore, deposition of sprayed irrigation water or soil on the surface of the vegetables is not considered in this analysis. However, vegetables grown on the soil that has been irrigated over a period of 30 years would incorporate some Ra-226. The concentration of Ra-226 in vegetables grown on irrigated soil is given by the equation

$$C_{veg} = C_{gw} * CF_{veg} = 8.66E-2 \text{ Bq g}^{-1} * 4E-2 * 1E3 \text{ g kg}^{-1} = 3.46 \text{ Bq/kg plant}$$

Where C_{veg} = concentration of Ra-226 in vegetation (Bq kg⁻¹ plant),
 C_S = concentration of Ra-226 in soil (8.7E-2 Bq g⁻¹),
 CF_{veg} = unitless concentration factor for Ra-226 (4E-2 Bq kg⁻¹ plant per Bq kg⁻¹ soil) (NCRP, 1999).

This should be considered a maximum plant concentration because the 30-year concentration of Ra-226 in the soil was used rather than an average value over that period.

EPA's Exposure Factor Handbook (EPA 2011) Table 9-3 lists vegetable consumption at 2.5 g kg⁻¹-d⁻¹ for a resident aged 20 to 49. For a 70 kg reference person, that would equate to 175 g d⁻¹ or 63.9 kg y⁻¹ of vegetable consumption. It is assumed that the resident would obtain 50% of their annual vegetable consumption from home-grown sources for a total consumption of 32 kg y⁻¹. The potential dose to a resident from eating irrigated vegetables containing Ra-226 is shown below:

$$D_{veg} = 32 \text{ kg y}^{-1} * C_{veg} * DCF = 3.96E-5 \text{ Sv y}^{-1} = 3.96 \text{ mrem y}^{-1},$$

Where D_{veg} = Dose from eating vegetables (mrem y⁻¹)
 C_{veg} = Concentration in vegetables (3.46 Bq kg⁻¹ plant), and
 DCF = Dose conversion factor (3.58E-7 Sv Bq⁻¹).

This dose is approximately 25% of the dose from drinking impacted well water.

The intake of Ra-226 from eating vegetables is equivalent to 32 kg y⁻¹ * 3.46 Bq kg⁻¹ = 111 Bq y⁻¹. Using foodstuff risk coefficients from Federal Guidance Report No. 13 (EPA, 1998), the thirty-year lifetime mortality risk to a resident from eating vegetables irrigated with well water would be as follows::

$$\text{Risk} = I_{veg} * T * RCF_f = 111 \text{ Bq y}^{-1} * 30 \text{ y} * 9.59 \text{ E-9 Bq}^{-1} = 3.18 \text{ E-5}$$

Where I_{veg} = Resident Ra-226 intake (111 Bq y⁻¹),
 RCF_f = Mortality risk coefficient factor, (9.59E-9 Bq⁻¹) and
 T = Length of consumption period (30 y).

Thirty-year lifetime morbidity risk to resident from eating vegetables may be calculated by:

$$\text{Risk} = I_U * T * RCF_m = 111 \text{ Bq y}^{-1} * 30 \text{ y} * 1.39\text{E-}8 \text{ Bq}^{-1} = 4.62\text{E-}5,$$

Where I_U = Ra-226 intake (111 Bq y⁻¹),
 RCF_m = Morbidity risk coefficient factor (1.39E-8- Bq⁻¹) and
 T = Length of consumption period (30 y).

3.1.3.4 Potential Dose and Risk to Resident from Eating Beef

The concentration of Ra-226 in beef from cattle drinking impacted water is given by the equation:

$$C_{\text{Beef}} = C_{\text{gw}} * Q_W * CF = 1.0 \text{ Bq L}^{-1} * 50 \text{ L d}^{-1} * 1\text{E-}3 \text{ d kg}^{-1} = 5 \text{ E-}2 \text{ Bq kg}^{-1},$$

Where C_{Beef} = Concentration of Ra-226 in beef (Bq kg⁻¹ beef),
 C_{GW} = Concentration of Ra-226 in well water (1 Bq L⁻¹),
 Q_{BW} = Quantity of water intake by cattle (50 L d⁻¹), and
 CF_{Beef} = Concentration factor for Ra-226 in Bq kg⁻¹ beef per Bq d⁻¹ intake (1E-3 d kg⁻¹ beef).

To estimate the potential concentration of Ra-226 in beef from eating forage grown on irrigated soil, the potential concentration of Ra-226 in the forage itself must be calculated. As mentioned above in the discussion of mechanisms for contamination of vegetables, forage may be impacted by two mechanisms: uptake from soil and direct deposition from irrigation water. In this case, both must be considered because forage would be fed to cattle on an unwashed basis.

Uptake of Ra-226 by forage from soil can be calculated using the following equation:

$$C_{\text{For-soil}} = C_S * CF_{\text{For}} = 8.66\text{E-}2 \text{ Bq g}^{-1} * 0.2 \text{ Bq kg}^{-1} (\text{forage}) / \text{Bq kg}^{-1} (\text{soil}) * 1\text{E}3 \text{ g kg}^{-1} = 17.3 \text{ Bq kg}^{-1},$$

Where $C_{\text{For-soil}}$ = Concentration in forage (Bq kg⁻¹),
 C_S = Concentration of Ra-226 in soil (8.66E-2 Bq g⁻¹),
 F_{For} = Forage concentration factor (0.2 Bq kg⁻¹ plant per Bq kg⁻¹ soil).

A fraction of the irrigation water sprayed onto the forage crop, assumed to be alfalfa, will be retained as surface contamination. This interception fraction is assumed to be 1%. It is further assumed that the deposition from the previous irrigation event will be washed off the surface and there will be no build up from irrigation event to subsequent irrigation event. So, the period of irrigation is assumed to be a single day. According to WBC (2015), the average yield of irrigated alfalfa hay during the period 2005 to 2008 was 3.3 tons per acre (t/ac). (For more recent years, the notation of cropping practice was discontinued and only total alfalfa yield was indicated.)

Using those conditions, the concentration of Ra-226 in forage from direct deposition by irrigation onto the surface of the plant may be calculated as follows:

$$C_{\text{For-irr}} = (C_{\text{GW}} * \text{IR} * \text{IP} * f) / Y = (1 \text{ Bq L}^{-1} * 5 \text{ L m}^{-2} \text{ d}^{-1} * 0.01 * 4.05\text{E}3 \text{ m}^2 \text{ ac}^{-1} * 1\text{E}3 \text{ g kg}^{-1}) / (3.3 \text{ ton ac}^{-1} * 9.08\text{E}5 \text{ g t}^{-1}) = 6.6\text{E}-2 \text{ Bq kg}^{-1} \text{ forage},$$

Where $C_{\text{For-irr}}$ = Concentration in forage from direct deposition (Bq kg⁻¹ forage),
 IR = Irrigation rate (5 L m⁻²-day),
 IP = Irrigation period (1 d),
 f = interception fraction (0.01)
 Y = Crop yield (3.3 ton ac⁻¹).

The concentration of Ra-226 in forage from soil uptake as well as direct deposition would be the sum of the two pathways for a total of 17.4 Bq kg⁻¹ forage.

It is unlikely that cattle will be fed alfalfa forage on a year-round basis. It is far more likely that the alfalfa will be used only as a supplement to pasture grass. However, for ease of calculation, it is assumed that irrigated forage consumption would continue on a year-round basis.

The concentration in beef from eating forage may be calculated as follows:

$$C_{\text{Beef}} = C_{\text{For}} * Q_{\text{For}} * CF_{\text{beef}} = 17.4 \text{ Bq kg}^{-1} * 12 \text{ kg d}^{-1} * 1\text{E}-3 \text{ d kg}^{-1} = 2.09\text{E}-1 \text{ Bq kg}^{-1},$$

Where C_{Beef} = Concentration of Ra-226 in beef (Bq kg⁻¹ beef),
 C_{For} = Concentration in forage (17.4 Bq kg⁻¹)
 Q_{For} = Quantity of forage intake by cattle (12 kg d⁻¹), and
 CF_{Beef} = Concentration factor for Ra-226 (1E-3 d kg⁻¹ beef).

The total concentration of radium in beef that results from livestock drinking well water and eating forage grown on soil irrigated with well water and from direct deposition of irrigation water on the forage is 0.259 Bq kg⁻¹ of meat.

EPA's Exposure Factor Handbook (EPA 2011) Table 11-4 lists meat consumption for a 20 to 49-year old to be 1.8 g kg⁻¹ d⁻¹ for the edible, uncooked portion. For a 70 kg reference person, that would equate to 126 g/day or 46 kg/yr of meat consumption. The potential dose to a resident from eating beef containing Ra-226 is shown below:

$$D_{\text{Beef}} = I_{\text{Beef}} * C_{\text{Beef}} * \text{DCF} = 46 \text{ kg y}^{-1} * 0.259 \text{ Bq kg}^{-1} * 3.58\text{E}-7 \text{ Sv Bq}^{-1} = 4.26\text{E}-6 \text{ Sv y}^{-1} = 4.26\text{E}-1 \text{ mrem y}^{-1},$$

Where D_{Beef} = Dose to resident from eating home grown beef (mrem y⁻¹)
 I_{Beef} = annual consumption of beef (46 kg y⁻¹),
 C_{Beef} = Ra-226 concentration in beef (0.259 Bq kg⁻¹), and
 DCF = 3.58 E-7 Sv Bq⁻¹.

The intake of Ra-226 from eating beef is equivalent to the annual consumption of beef, 46 kg y⁻¹, multiplied by the Ra-226 concentration in beef, 0.259 Bq kg⁻¹, for a total of 11.9 Bq y⁻¹. Using foodstuff risk coefficients from Federal Guidance Report No. 13 (EPA, 1998), the thirty-year lifetime mortality risk to a resident from eating beef may be calculated by:

$$\text{Risk} = I_{\text{Beef}} * T * \text{RCF}_f = 11.9 \text{ Bq y}^{-1} * 30 \text{ y} * 9.56 \text{ E}-9 \text{ Bq}^{-1} = 3.41 \text{ E}-6,$$

Where I_{Bee} = Resident Ra-226 intake (11.9 Bq y⁻¹),
 RCF_f = Mortality risk coefficient factor, (1.39 E-8 Bq⁻¹) and
 T = Length of consumption period (30 y).

The thirty-year lifetime morbidity risk to resident from eating beef may be calculated by:

$$\text{Risk} = I_U * T * RCF_m = 11.9 \text{ Bq y}^{-1} * 30 \text{ y} * 1.39 \text{ E-8 Bq}^{-1} = 4.96 \text{ E-6},$$

Where I_U = Ra-226 intake (5.69 Bq y⁻¹),
 RCF_m = Morbidity risk coefficient factor (2.46 E-9 Bq⁻¹) and
 T = Length of consumption period (30 y).

3.1.3.5 Summary of Ra-226 Radiation Effects

Table 3 is a summary of the calculated dose and risk estimates from intake of Ra-226 contained in well water, assuming 1.0 Bq L⁻¹ of water. Dose and risk are dominated by the drinking water pathway. The impact from eating vegetables and beef that resulted from irrigating with well water is only about 2.5% of that from drinking well water.

On a per Bq basis, the dose represented by Ra-226 is over six times greater than that represented by uranium for the same exposure scenario. Both the mortality and morbidity risks presented by Ra-226 are nearly eight times higher than the mortality risk presented by the uranium intake.

Table 3 Summary of doses and risks calculated from use of impacted well water containing Ra-226.

Exposure Pathway	Calculated Dose (mrem/yr)	30-year Risk Estimate (/yr)	
		Mortality	Morbidity
Drinking water	1.61E+01	9.66E-05	1.40E-04
Eating vegetables	3.97E+00	3.18E-05	4.62E-05
Eating beef	4.26E-01	3.41E-06	4.96E-06
Bathing			
Total	2.05E+01	1.32E-04	1.91E-04

3.1.4 Selenium

The assumptions for consideration of potential effects from selenium in the well water, are similar to those used when considering toxicity of arsenic and uranium:

- All drinking, irrigation and bathing water comes from same potentially impacted well,
- The nominal selenium concentration is 1.0 E-3 mg L⁻¹
- Cattle directly consume well water and forage irrigated with well water,
- The resident farmer consumes beef fed with irrigated forage

- The resident bathes in water from the well.

The adverse health effect of exposure to selenium is limited to systemic toxicity. Selenium is not known to be a carcinogen. Selenium is an essential element in trace quantities. However, at excessive levels, selenium may be toxic to humans. According to the ATSDR Toxicological Profile for selenium “a minimum dietary level of selenium is required for good health” (ATSDR, 2003). ATSDR also states that “Even if mildly excessive amounts of selenium are eaten over long periods, brittle hair and deformed nails can develop. In extreme cases, people may lose feeling and control in arms and legs.” (ATSDR, 2003)

As with uranium and arsenic, unless otherwise noted, exposure parameters are taken from NRC Report No. 123 (1986) and the EPA Exposure Factors Handbook (2011). The equations used to calculate concentrations in foodstuffs and intakes are the same for selenium as for uranium and arsenic toxicity. As noted above, selenium is not a known carcinogen.

3.1.4.1 Potential Risk from Drinking Impacted Groundwater

Drinking impacted groundwater is the primary exposure pathway. The potential annual selenium intake to a resident from direct ingestion of groundwater at the nominal concentration of 1.0E-3 mg L⁻¹ is as follows:

$$\text{Daily Intake, } I_{\text{Se}} = C_w * I_w = 1\text{E-3 mg L}^{-1} * 1.23 \text{ L d}^{-1} = 1.23 \text{ E-3 mg d}^{-1}$$

where

I_{Se}	=	Resident selenium intake (mg y ⁻¹)
C_w	=	Selenium concentration in well water (1.0 E-3 mg L ⁻¹)
I_w	=	Resident intake of water (EPA, 2011)

The reference dose for selenium is 5 E-3 mg kg⁻¹ d⁻¹ (EPA, 2017)

The hazard quotient for direct ingestion of Se in drinking water at the nominal concentration would be as follows:

$$\text{HQ} = 1.23 \text{ E-3 mg d}^{-1} / (70 \text{ kg} * 5 \text{ E-3 mg kg}^{-1} \text{ d}^{-1}) = 3.5 \text{ E-3}$$

3.1.4.2 Buildup of Selenium in Soil

Irrigating with impacted water could lead to increased concentrations in the surface soil and uptake in both vegetables and forage. The average daily increase in selenium concentration in soil at a nominal groundwater concentration of 1.0E-3 mg L⁻¹ can be calculated as follows:

$$I_s = (IR * C_{\text{GW}} * IP) / (MD * \rho * 365 \text{ d y}^{-1} * 1 \text{ E4 cm}^2 \text{ m}^{-2}) = 9.13 \text{ E-9 mg g}^{-1}$$

Where

I_s	=	Intake to soil (mg g ⁻¹)
C_{GW}	=	Selenium concentration in water (1.0 E-3 mg L ⁻¹)
IR	=	Rate of irrigation (5 L m ⁻² d ⁻¹),
MD	=	Soil mixing depth (15 cm),
IP	=	Irrigation period (150 d y ⁻¹),
ρ	=	Soil density (1.5 g cm ⁻³).

The selenium in soil will accumulate over time with each added year of irrigation. However, the selenium will also be removed from the soil by leaching and uptake in plants. The concentration in the soil will increase to an equilibrium level over time as follows:

$$C_{Seq} = I_S \lambda_S^{-1} = 9.13 \text{ E-9 mg g}^{-1} \text{ d}^{-1} / 2.70 \text{ E-5 d}^{-1} = 3.38 \text{ E-4 mg g}^{-1}$$

Where C_{Seq} = Soil concentration at equilibrium (mg g⁻¹),
 λ_S = Soil removal constant (leaching and uptake) = 2.70E-5 d⁻¹ (NCRP, 1999).

Over the course of the 30-yr duration of this analysis, the soil concentration will build up to:

$$C_S = C_{Seq} * (1 - e^{-\lambda t}) = 3.38 \text{ E-04 mg g}^{-1} (1 - e^{-9.86\text{E-3} * 30}) = 8.66 \text{ E-5 mg g}^{-1},$$

This concentration will be used for subsequent calculations risk from eating irrigated vegetables and beef.

3.1.4.3 Potential Risk to Resident from Irrigated Vegetables

Plants grown in an irrigated garden would be subject to contamination from external deposition of sprayed water or from uptake of selenium from the soil. It is unlikely that sprayed vegetables would be eaten without washing; therefore deposition of sprayed irrigation water or soil on the surface of the vegetables is not considered in this analysis. However, vegetables grown on the soil that has been irrigated over a period of 30 years would incorporate some selenium. The concentration of selenium in vegetables grown on irrigated soil is given by the equation:

$$C_{veg} = C_{gw} * CF_{veg} = 8.66\text{E-5 mg g}^{-1} * 1.0\text{E-1} * 1 \text{ E3 g kg}^{-1} = 8.66 \text{ E-3 mg kg}^{-1} \text{ plant}$$

Where C_{veg} = concentration of Se in vegetation (mg kg⁻¹ plant),
 C_S = concentration of Se in soil (8.66 E-5 mg g⁻¹),
 CF_{veg} = unitless concentration factor for Se (0.1 mg kg⁻¹ plant per mg kg⁻¹ soil) (NCRP, 1999).

This should be considered a maximum plant concentration because the 30-year concentration of selenium in the soil was used rather than an average value over that period.

The Exposure Factors Handbook (EPA 2011) Table 9-3 lists vegetable consumption at 2.5 g kg⁻¹·d⁻¹ for a resident aged 20 to 49. For a 70 kg reference person, that would equate to 175 g d⁻¹ or 63.9 kg y⁻¹ of vegetable consumption. It is assumed that the resident would obtain 50% of their annual vegetable consumption from home-grown sources for a total consumption of 32 kg y⁻¹.

The estimated average daily intake from consumption of vegetables grown in soil irrigated with water at the nominal selenium concentration of 1 E-3 mg L⁻¹ would be as follows:

$$I_{veg} = 8.66 \text{ E-3 mg kg}^{-1} * 32 \text{ kg y}^{-1} / 365 \text{ d y}^{-1} = 7.59 \text{ E-4 mg d}^{-1}$$

The HQ would be as follows:

$$HQ = 7.59 \text{ E-4 mg d}^{-1} / (70 \text{ kg} * 5 \text{ E-3 mg kg}^{-1} \text{ d}^{-1}) = 2.17 \text{ E-3}$$

3.1.4.4 Potential Risk to Resident from Eating Beef

The concentration of selenium in beef from cattle drinking impacted water is given by the equation:

$$C_{Beef} = C_{gw} * Q_W * CF = 1.0 \text{ E-3 mg L}^{-1} * 50 \text{ L d}^{-1} * 0.10 \text{ d kg}^{-1} = 5.0 \text{ E-3 mg kg}^{-1},$$

Where C_{Beef} = Concentration of selenium in beef (mg kg^{-1} beef),
 C_{GW} = Concentration of selenium in well water (1E-3 mg L^{-1}),
 Q_{BW} = Quantity of water intake by cattle (50 L d^{-1}), and
 CF_{Beef} = Concentration factor for selenium in mg kg^{-1} beef per mg d^{-1} intake (0.1 kg^{-1} beef) (NCRP, 1996).

To estimate the potential concentration of selenium in beef from eating forage grown on irrigated soil, the potential concentration of selenium in the forage itself must be calculated. As mentioned above in the discussion of mechanisms for contamination of vegetables, forage may be impacted by two mechanisms: uptake from soil and direct deposition from irrigation water. In this case, both must be considered because forage would be fed to cattle on an unwashed basis.

Uptake of selenium by forage from soil can be calculated using the following equation:

$$C_{For-soil} = C_S * CF_{For} = 8.66\text{E-5 mg g}^{-1} * 0.50 * 1\text{E3 g kg}^{-1} = 4.33 \text{ E-2 mg kg}^{-1},$$

Where $C_{For-soil}$ = Concentration in forage (mg kg^{-1}),
 C_S = Concentration of selenium in soil (8.66E-5 mg g^{-1}),
 F_{For} = Forage concentration factor (0.5 mg kg^{-1} plant per mg kg^{-1} soil) (NCRP, 1996).

A fraction of the selenium in irrigation water sprayed onto the forage crop, assumed to be alfalfa, will be retained as surface contamination. This interception fraction is assumed to be 1%. It is further assumed that the deposition from the previous irrigation event will be washed off the surface and there will be no build-up of arsenic from an irrigation event to subsequent irrigation events. So, the period of irrigation is assumed to be a single day. According to WBC (2015), the average yield of irrigated alfalfa hay during the period 2005 to 2008 was 3.38 tons per acre (t ac^{-1}). (For more recent years, the notation of cropping practice was discontinued and only total alfalfa yield was indicated.)

Using those conditions, the concentration of selenium in forage from direct deposition by irrigation onto the surface of the plant may be calculated as follows:

$$C_{For-irr} = (C_{GW} * IR * IP * f) / Y = (1.0 \text{ E-3 mg L}^{-1} * 5 \text{ L m}^{-2} \text{ d}^{-1} * 0.01 * 4.05\text{E3 m}^2 \text{ ac}^{-1} * 1\text{E3 g kg}^{-1}) / (3.38 \text{ ton ac}^{-1} * 9.08\text{E5 g t}^{-1}) = 6.6 \text{ E-5 mg kg}^{-1} \text{ forage},$$

Where $C_{\text{For-irr}}$ = Concentration in forage from direct deposition (mg kg^{-1} forage),
 IR = Irrigation rate ($5 \text{ L m}^{-2}\text{-day}$),
 IP = Irrigation period (1 d),
 f = interception fraction (0.01)
 Y = Crop yield (3.38 ton ac^{-1}).

The concentration of selenium in forage from soil uptake as well as direct deposition is the sum of the two pathways for a total of $4.3 \text{ E-2 mg kg}^{-1}$ forage.

It is unlikely that cattle will be fed alfalfa forage on a year-round basis. It is far more likely that the alfalfa will be used only as a supplement to pasture grass. However, for ease of calculation, it is assumed that irrigated forage consumption would continue on a year-round basis.

The selenium concentration in beef from eating forage may be calculated as follows:

$$C_{\text{Beef}} = C_{\text{For}} * Q_{\text{For}} * CF_{\text{beef}} = 4.3 \text{ E-2 mg kg}^{-1} * 12 \text{ kg d}^{-1} * 0.10 \text{ d kg}^{-1} = 5.2 \text{ E-2 mg kg}^{-1},$$

Where C_{Beef} = Concentration of selenium in beef (mg kg^{-1} beef),
 C_{For} = Concentration in forage ($1.74\text{E-5 mg kg}^{-1}$)
 Q_{For} = Quantity of forage intake by cattle (12 kg d^{-1}), and
 CF_{Beef} = Concentration factor for selenium (0.1 d kg^{-1} beef)(NCRP, 1999).

The total concentration of selenium in beef that results from livestock drinking well water and eating forage grown on soil irrigated with well water and from direct deposition of irrigation water on the forage is $5.2 \text{ E-2 mg kg}^{-1}$ of meat.

The total selenium concentration in beef directly consuming well water and consuming forage irrigated with well water would be as follows:

$$C_{\text{beef}} = 5.2 \text{ mg kg}^{-1} \text{ (forage)} + 5.0 \text{ E-3 mg kg}^{-1} \text{ (water)} = 5.7 \text{ E-2 mg kg}^{-1}$$

EPA's Exposure Factors Handbook (EPA 2011) Table 11-4 lists meat consumption for a 20 to 49 year old to be $1.8 \text{ g kg}^{-1} \text{ d}^{-1}$ for the edible, uncooked portion. For a 70 kg reference person, that would equate to 126 g d^{-1} (0.126 kg d^{-1}) or 46 kg/yr of meat consumption.

The HQ for consumption of beef consuming well water and forage at a selenium concentration of $1.0 \text{ E-3 mg L}^{-1}$ would be as follows:

$$HQ = 0.126 \text{ kg d}^{-1} * 5.7 \text{ E-2 mg Se kg}^{-1} \text{ beef} / (70 \text{ kg} * 5 \text{ E-3 mg Se kg}^{-1} \text{ d}^{-1}) = 2.1 \text{ E-2}$$

The HQ for all three pathways summed is as follows:

$$HQ \text{ (water)} + HQ \text{ (vegetables)} + HQ \text{ (beef)} = 0.0035 + 0.0022 + 0.021 = 0.027$$

3.1.4.5 Risk from Selenium Concentration in Groundwater at the POE

Geochemical modeling has demonstrated that the selenium concentrations at the aquifer exemption boundary will not be elevated in the future as a result of Mine Unit 1 operations (Enchemica, 2017). Therefore, no risk calculation was performed for the POE.

3.2 Doses and Risks at the Point of Compliance (POC) Under Present and Modeled Future Concentrations

The Alternate Concentration Limit (ACL) analysis demonstrates that under existing and modeled future conditions, the groundwater poses no human health or environmental risk at the Point of Exposure (POE). The POE for Mine Unit 1 is at the aquifer exemption boundary, 150 feet outside of the ring of monitoring wells as per the Smith Ranch license and permits. The transport model for this ACL application predicts that there will be no measurable increase in dissolved uranium concentrations at the POE for any of the six flow pathways modeled. The estimated dose to a member of the public would be less than 0.001 mrem per year (mrem y⁻¹)

The groundwater within the well field was not suitable for human consumption prior to Smith Ranch operations as demonstrated by the baseline interior ore zone monitoring well data. The only reasonable potential use of such groundwater is for stock watering. The following dose and risk analysis was performed for the median current constituent concentration in the well showing the highest average uranium and arsenic values over the previous three years, B-004 and for a projected median concentration for all modeled wells within 1,000 years.

3.2.1 Dose and Risk Under Current Conditions

3.2.1.1 Dose and Risk from Uranium

The three-year median concentration of uranium in B-004 is 3.32 mg L⁻¹; the median arsenic concentration in B-004 is 0.0275 mg L⁻¹. (Note: the average concentrations are 3.77 mg L⁻¹ and 0.0268 mg L⁻¹, respectively.) Ra-226 was not considered in this analysis as the median and mean Ra-226 concentration in B-004, 670 pCi L⁻¹, is less than the average baseline concentration for the interior ore zone, 726 pCi/L⁻¹ (Enchemica, 2017).
Uranium Cancer Dose and Risk

The uranium concentration in beef cattle drinking groundwater from well B-004 under current conditions would be as follows:

$$C_{\text{beef}} = C_{\text{water}} * TC * I_{\text{gw}}$$

Where: C_{beef} = concentration of uranium in beef

C_{water} = median concentration of uranium in groundwater = 3.32 mg L⁻¹

I_w = daily intake of water by beef cattle = 50 L d⁻¹ (NCRP, 1988)
TC = transfer coefficient for uranium in beef = 0.0008 d kg⁻¹ (NCRP 1988)

$$C_{\text{beef}} = 3.32 \text{ mg L}^{-1} * 50 \text{ L d}^{-1} * 0.0008 \text{ d kg}^{-1} = 0.13 \text{ mg kg}^{-1}$$

The estimated daily intake of uranium by a beef consumer would be as follows:

$$I_U = C_{\text{beef}} * I_{\text{beef}}$$

Where: I_{beef} = daily intake of beef = 1.8 g kg⁻¹ d⁻¹ (EPA, 2011)
 I_U = daily intake of uranium by the beef consumer

$$I_U = [0.13 \text{ mg (U-nat) kg}^{-1}(\text{beef})] * [1.8 \text{ g}(\text{beef}) \text{ kg}^{-1} \text{ d}^{-1} * 70 \text{ kg}] * [1 \text{ E-3 kg g}^{-1}(\text{beef})] \\ = 1.7 \text{ E-2 mg (U-nat) d}^{-1}$$

Assuming an exposure frequency of 350 d y⁻¹, the annual U-nat intake from consuming beef would be 6.1 mg y⁻¹. The specific activity of natural uranium (U-nat) is equal to 25 Bq mg⁻¹.

$$\text{U-nat intake} = 1.7\text{E-2 mg d}^{-1} * 350 \text{ d y}^{-1} * 25 \text{ Bq mg}^{-1} = 1.5 \text{ E2 Bq y}^{-1}$$

The dose coefficient for U-nat from EPA Federal Guidance No. 11 (EPA, 1988) is: 7.27E-8 Sv Bq⁻¹.

[Note: Dose and Risk Coefficients for U-nat are the average of the coefficients listed In EPA Federal Guidance Reports #11 and 13 (EPA 1988, 1999) for ²³⁴U and ²³⁸U as it is assumed that the two isotopes in groundwater attributable to Smith Ranch would be in equilibrium.]

The annual dose from ingestion of 1.5 E2 Bq U-nat would be as follows:

$$\text{Dose} = 1.5 \text{ E2 Bq y}^{-1} * 7.27\text{E-8 Sv Bq}^{-1} * 1.0\text{E5 mrem Sv}^{-1} = 1.1 \text{ mrem y}^{-1}$$

The lifetime risk from consuming beef watered from Well B-004 due to uranium ingestion, calculated assuming an exposure duration of 30 years, would be as follows:

$$\text{Total U-nat consumed from beef} = 30 \text{ y} * 1.5 \text{ E2 Bq y}^{-1} = 4.5 \text{ E3 Bq}$$

The lifetime risk coefficients for cancer mortality and cancer morbidity from EPA Federal Guidance Report No. 13 (EPA, 1999) are as follows:

$$\text{Cancer risk (mortality)} = 1.59 \text{ E-9 Bq}^{-1} \\ \text{Cancer risk (morbidity)} = 2.46 \text{ E-9 Bq}^{-1}$$

The lifetime cancer risks for ingestion of beef consuming groundwater from Well B-004 would be as follows:

$$\text{Lifetime Risk (cancer mortality)} = 4.5 \text{ E3 Bq} * .59 \text{ E-9 Bq}^{-1} = 7.2 \text{ E-6}$$

$$\text{Lifetime Risk (cancer morbidity)} = 4.5 \text{ E3 Bq} * .46 \text{ E-9 Bq}^{-1} = 1.1 \text{ E-5}$$

A Derived Concentration Guideline Level (DCGL) for water at the point of compliance based on the dose under the most reasonable exposure scenario, beef consumption of groundwater, assuming a criterion of 25 mrem y⁻¹ would be as follows:

$$DCGL = 25 \text{ mrem y}^{-1} * 3.32 \text{ mg L}^{-1} / 1.1 \text{ mrem y}^{-1} = 75 \text{ mg L}^{-1}$$

3.2.1.2 Uranium Chemical Toxicity

Uranium is chemically toxic to the kidneys as well as being radioactive. The chemical toxicity of uranium is generally the limiting factor for soluble ingested uranium. The measure of adverse health impacts from chemical toxicants is the Hazard Quotient (HQ). The HQ is the average daily intake divided by the reference dose (RfD). The RfD is the daily intake at which no adverse effects are expected. It is based on the lowest observed adverse effect level (LOAEL) or the no observed adverse effect level (NOAEL) derived from human and animal studies. Depending on the quality of the data and applicability to humans, the LOAEL or NOAEL is divided by a safety factor that can range from 10 to 1,000 to obtain the RfD. The current RfD for uranium is 0.0002 mg kg⁻¹ d⁻¹ based on the 2017 EPA Regional Screening Levels (RSLs), a 15 fold increase from the 2016 RSLs (EPA, 2017).

The HQ for uranium in beef drinking groundwater from Well B-004 would be as follows:

$$HQ = 1.7E-2 \text{ mg d}^{-1} / (70 \text{ kg} * 2E-4 \text{ mg kg d}^{-1}) = 1.2$$

A HQ greater than 1.0 does not necessarily indicate adverse health effects; however, a HQ less than 1.0 is generally considered a safe daily intake.

A DCGL for uranium based on chemical toxicity would be as follows:

$$DCGL = 3.32 \text{ mg L}^{-1} * 1.0 / 1.2 = 2.8 \text{ mg L}$$

3.2.1.3 Arsenic Toxicity and Risk

Arsenic is a carcinogen in addition to being toxic. Therefore, the cancer risk and the HQ are calculated for arsenic.

The arsenic concentration in beef cattle drinking groundwater from well B-004 under current conditions would be as follows:

$$C_{\text{beef}} = C_{\text{water}} * TC * I_{\text{gw}}$$

Where: C_{beef} = concentration of arsenic in beef

C_{water} = median concentration of arsenic in groundwater = 0.0275 mg L⁻¹

I_w = daily intake of water by beef cattle = 50 L d⁻¹ (NCRP, 1988)

TC = transfer coefficient for arsenic in beef = 0.02 d kg⁻¹ (NCRP 1988)

$$C_{\text{beef}} = 0.0275 \text{ mg L}^{-1} * 50 \text{ L d}^{-1} * 0.02 \text{ d kg}^{-1} = 0.0275 \text{ mg kg}^{-1}$$

The estimated daily intake of arsenic by a beef consumer would be as follows:

$$I_{As} = C_{beef} * I_{beef}$$

Where: I_{beef} = daily intake of beef = 1.8 g kg⁻¹ d⁻¹(EPA, 2011)

$$I_{As} = [0.0275 \text{ mg (As) kg}^{-1}(\text{beef})] * [1.8 \text{ g}(\text{beef}) \text{ kg}^{-1} \text{ d}^{-1}] * [1\text{E-3 kg}(\text{beef}) \text{ g}^{-1}(\text{beef})]= 4.95 \text{ E-5 mg(As) kg}^{-1} \text{ d}^{-1}$$

The cancer slope factor for inorganic arsenic is 1.5 (mg kg⁻¹ d⁻¹)⁻¹.

Therefore, the risk is as follows:

$$\text{Risk} = 4.95 \text{ E-5 mg(As) kg}^{-1} \text{ d}^{-1} * 1.5 (\text{mg kg}^{-1} \text{ d}^{-1})^{-1} = 7.4 \text{ E-5}$$

The HQ is the ratio of the average daily intake to the Reference Dose.

$$\text{RfD for As} = 0.0003 \text{ mg kg}^{-1} \text{ d}^{-1}(\text{EPA, 2017})$$

$$\text{HQ} = 4.95 \text{ E-5 mg(As) kg}^{-1} \text{ d}^{-1} / 0.0003 \text{ mg kg}^{-1} \text{ d}^{-1} = 0.17$$

Based on the HQ, a reasonable Derived Concentration Guideline Limit (DCGL) for As would be as follows:

$$\text{DCGL} = 1.0 * 0.0275 \text{ mg L}^{-1} / 0.17 = 0.16 \text{ mg L}^{-1}$$

3.2.1.4 Ra-226 Radiation Dose and Risk

The Ra-226 average concentration in the Mine Unit 1 POC groundwater samples is indistinguishable from the baseline concentrations. The dose and risks are calculated for completeness; however, they are not applicable to the ACL risk analysis. The Ra-226 concentration in beef cattle drinking groundwater from well B-004 under current conditions would be as follows:

$$C_{beef} = C_{water} * TC * I_{gw}$$

Where: C_{beef} = concentration of Ra-226 in beef

C_{water} = concentration of R-2226 in groundwater = 670 pCi L⁻¹

I_w = daily intake of water by beef cattle = 50 L d⁻¹(NCRP, 1988)

TC = transfer coefficient for Ra-226 in beef = 0.001 d kg⁻¹(NCRP 1988)

$$C_{beef} = 670 \text{ mg L}^{-1} * 50 \text{ L d}^{-1} * 0.001 \text{ d kg}^{-1} = 34 \text{ pCi kg}^{-1}$$

The estimated daily intake of Ra-226 by a beef consumer would be as follows:

$$I_{Ra} = C_{beef} * I_{beef}$$

Where: I_{beef} = daily intake of beef = 1.8 g kg⁻¹ d⁻¹(EPA, 2011)

$$I_{Ra} = [34 \text{ pCi (Ra-226) kg}^{-1}(\text{beef})] * [1.8 \text{ g}(\text{beef}) \text{ kg}^{-1} \text{ d}^{-1} * 70 \text{ kg}] * [1 \text{E-3 kg}(\text{beef}) \text{ g}^{-1}(\text{beef})] = 4.3 \text{ pCi (Ra-226) d}^{-1}$$

Assuming an exposure frequency of 350 d y⁻¹, the annual intake would be 1.5 E3 pCi y⁻¹. The conversion factor for pCi to Bq is 0.037. Therefore, the annual intake would be 56 Bq.

The dose coefficient for Ra-226 from EPA Federal Guidance Report No. 11 is 3.58 E-7 Sv Bq⁻¹

Therefore, the annual dose from Ra-226 due to ingestion of beef watered with groundwater from B-004 would be as follows:

$$\text{Dose} = 56 \text{ Bq y}^{-1} * 3.58 \text{E-7 Sv Bq}^{-1} * 1.0 \text{E5 mrem Sv}^{-1} = 2.0 \text{ mrem y}^{-1}$$

The lifetime risk from ingestion of beef watered with groundwater from Well B-004, assuming a 30-year exposure duration would be as follows:

$$\text{Intake of Ra-226} = 56 \text{ Bq y}^{-1} * 30 \text{ y} = 1.7 \text{ E3 Bq}$$

The lifetime risk coefficients for cancer mortality and cancer morbidity from EPA Federal Guidance Report No. 13 are as follows:

$$\text{Cancer risk (mortality)} = 9.56 \text{ E-9 Bq}^{-1}$$

$$\text{Cancer risk (morbidity)} = 1.39 \text{ E-8 Bq}^{-1}$$

The lifetime risks would be as follows:

$$\text{Lifetime Risk (cancer mortality)} = 1.7 \text{ E3 Bq} * 9.59 \text{ E-9 Bq}^{-1} = 1.6 \text{ E-5}$$

$$\text{Lifetime Risk (cancer morbidity)} = 1.7 \text{ E3 Bq} * 1.39 \text{E-8 Bq}^{-1} = 2.4 \text{ E-5}$$

3.2.1.5 *Sum of the Risks and HQ for Ingesting Beef Consuming Groundwater from Well B-004*

The cancer risks and potential for non-cancer adverse health effects attributable to eating beef that are watered from Well B-004 in the Mine Unit 1 well field are summarized in Table 4.

Table 4 Summary of cancer risks and non-cancer health risks from well B-004 under current conditions.

Constituent	Annual Dose (mrem y ⁻¹)	Cancer Morbidity	Hazard Quotient
Uranium	1.1	1.1E-5	1.2
Arsenic	Not applicable	7.5E-5	0.17
Total	1.2	8.6E-5	1.4 (Hazard Index)
<i>Ra-226</i>	<i>2.0</i>	<i>2.4E-5</i>	<i>Not applicable</i>

(Cancer morbidity was used as the measure of risk for both uranium and arsenic for consistency. The slope factor for arsenic is defined as the risk of cancer not necessarily the risk of cancer mortality.)

Radium-226 was evaluated in the risk assessment as it has a significant impact. However, the existing Ra-226 concentrations are at or below the baseline concentration.

Ingestion of beef from cattle consuming water from a stock tank at the median concentration in B-004, the well with the highest concentrations, would not pose an unacceptable risk above the baseline risk. The sum of the lifetime cancer risks is less than 1E-4, the upper end of the range of acceptable cancer risks. While the Hazard Index is greater than one, it does not necessarily mean that health effects are probable. In general, the RfD includes a safety factor of 10 or greater. The primary contributor to cancer mortality is arsenic. The primary contributor to non-cancer health effects, as measured by the HQ, is uranium. Radium-226 would contribute to the annual dose and lifetime risk but, as noted above, the Ra-226 concentration in Well B-004 is less than the baseline concentration for the interior ore zone wells.

3.2.1.6 Selenium Toxicity and Risk

As noted above, selenium is an essential element for human health; however, at high levels, it can be toxic. Selenium is not known to be a carcinogen. Therefore, only the HQ is calculated for selenium.

The highest measured concentration of Se in 2017 in MU 1 wells was 0.021 in B13 (March 2017). However, a concentration of 0.099 mg L⁻¹ was measured in 2015. The concentrations have declined since that time. The concentration in beef consuming groundwater at a Se concentration of 0.021 mg L⁻¹ would be as follows:

$$C_{\text{beef}} = C_{\text{water}} * TC * I_{\text{gw}}$$

Where: C_{beef} = concentration of arsenic in beef

C_{water} = maximum measured concentration of Se in groundwater = 0.021 mg L⁻¹

I_{w} = daily intake of water by beef cattle = 50 L d⁻¹ (NCRP, 1996)

TC = transfer coefficient for selenium in beef = 0.1 d kg⁻¹ (NCRP 1996)

$$C_{\text{beef}} = 0.021 \text{ mg L}^{-1} * 50 \text{ L d}^{-1} * 0.1 \text{ d kg}^{-1} = 0.11 \text{ mg kg}^{-1}$$

The estimated daily intake of selenium by a beef consumer would be as follows:

$$I_{\text{As}} = C_{\text{beef}} * I_{\text{beef}}$$

Where: I_{beef} = daily intake of beef = 1.8 g kg⁻¹ d⁻¹ (EPA, 2011)

$$I_{\text{Se}} = [0.11 \text{ mg (Se) kg}^{-1} (\text{beef})] * [1.8 \text{ g (beef) kg}^{-1} \text{ d}^{-1}] * [1\text{E-3 kg g}^{-1}] = 1.9 \text{ E-4 mg (Se) kg}^{-1} \text{ d}^{-1}$$

The HQ is the ratio of the average daily intake to the Reference Dose.

$$\text{RfD for Se} = 0.005 \text{ mg kg}^{-1} \text{ d}^{-1} \text{ (EPA, 2017)}$$

$$\text{HQ} = 1.9 \text{ E-4 mg(Se) kg}^{-1} \text{ d}^{-1} / 0.005 \text{ mg kg}^{-1} \text{ d}^{-1} = 0.038$$

The proposed ACL for Se at the Point of Compliance is 0.2 mg L⁻¹. The HQ is directly proportional to the Se concentration in water. Therefore, the HQ for the ACL would be as follows:

$$\text{HQ (0.2 mg L}^{-1} \text{ Se)} = 0.038 (0.2 \text{ mg L}^{-1} / 0.021 \text{ mg L}^{-1}) = 0.36$$

3.2.2 Dose and Risks for Modeled Future Concentration

3.2.2.1 Dose and Risk from Uranium

The maximum modeled uranium concentrations in B-004 range from 13 mg L⁻¹ (years 777-1,000) at an initial pH of 7.0 to 51 mg L⁻¹ (years 463-742) at an initial pH of 6.3. A maximum concentration between those two extremes is assumed to be the most reasonable estimate. The maximum modeled concentration at an initial pH of 6.7 is 27 mg L⁻¹. The dose and risk are directly proportional to the uranium concentration. Therefore, based on the dose and risks at a concentration of 3.32 mg L⁻¹, the dose and risks at the maximum modeled concentration would be as follows:

$$\text{Dose at } 27 \text{ mg L}^{-1} = 1.1 \text{ mrem y}^{-1} * 27 \text{ mg L}^{-1} / 3.32 \text{ mg L}^{-1} = 8.9 \text{ mrem y}^{-1}$$

$$\text{Cancer Risk (morbidity)} = 1.1 \text{ E-}5 * 27 \text{ mg L}^{-1} / 3.32 \text{ mg L}^{-1} = 8.9 \text{ E-}5$$

$$\text{Hazard Quotient} = 1.2 * 27 \text{ mg L}^{-1} / 3.32 \text{ mg L}^{-1} = 9.7$$

It is unlikely that the groundwater from B-004 would be used in the future. However, the dose and risk were calculated for completeness. The ACL is based on the potential dose at the designated POE not the POC.

3.2.2.2 Risk from Arsenic

The maximum modeled arsenic concentration in B-004 is 0.039 mg L⁻¹ at 394 years (Enchemica, 2017). The estimated cancer risk and HQ are as follows:

$$\text{Cancer Risk at } 0.039 \text{ mg L}^{-1} = \text{Risk at } 0.0275 \text{ mg L}^{-1} * 0.039 \text{ mg L}^{-1} / 0.0275 \text{ mg L}^{-1}$$

$$\text{Cancer Risk at } 0.0275 \text{ mg L}^{-1} = 7.5 \text{ E-}5$$

$$\text{Cancer Risk at } 0.039 \text{ mg L}^{-1} = 7.5 \text{ E-}5 * (0.039 \text{ mg L}^{-1} / 0.0275 \text{ mg L}^{-1}) = 1.1 \text{ E-}4$$

The HQ would be as follows:

$$\text{HQ} = 0.17 * (0.039 \text{ mg L}^{-1} / 0.0275 \text{ mg L}^{-1}) = 0.24$$

3.2.2.3 Dose and Risk from Ra-226

The dose and risk from Ra-226 at a nominal future potential concentration of 1,000 pCi L⁻¹ can be calculated by scaling up the calculated value at the current POC concentration of 670 pCi L⁻¹.

$$\text{Annual dose} = 20.5 \text{ mrem y}^{-1} * 1,000 \text{ pCi g}^{-1} / 670 \text{ pCi g}^{-1} = 30.6 \text{ mrem y}^{-1}$$

The estimated morbidity risk after 30 years of exposure would be as follows:

$$\text{Risk} = 1.9 \text{ E-}4 * 1,000 \text{ pCi L}^{-1} / 670 \text{ pCi L}^{-1} = 2.8 \text{ E-}4$$

Table 5 Summary of cancer risks and non-cancer health risks from well B-004 under future conditions.

Constituent	Annual Dose (mrem y ⁻¹)	Cancer Morbidity	Hazard Quotient
Uranium	8.9	8.9E-5	9.7
Arsenic	Not applicable	1.1E-4	0.24
Total	8.9	2.0E-4	9.9 (Hazard Index)
<i>Ra-226</i>	<i>30.6</i>	<i>2.8E-4</i>	<i>Not applicable</i>

Radium-226 was evaluated in the risk assessment as it has a significant impact on the potential risk to an individual accessing the MU-1 groundwater. However, the existing Ra-226 concentrations are at or below the baseline concentration.

Ingestion of beef from cattle consuming water from a stock tank at the median concentration in B-004, the well with the highest concentrations, would not pose an unacceptable risk above the baseline risk. The sum of the lifetime cancer risks is less than 1E-4, the upper end of the range of acceptable cancer risks. While the Hazard Index is greater than one, it does not necessarily mean that health effects are probable. In general, the RfD includes a safety factor of 10 or greater. The primary contributor to the cancer risk is arsenic. The primary contributor to non-cancer health effects, as measured by the HQ, is uranium. Radium-226 would contribute to the annual dose and lifetime risk but, as noted above, the existing Ra-226 concentration in Well B-004 is less than the baseline concentration for the interior ore zone wells.

3.2.2.4 Dose and Risk from Selenium

Selenium concentrations in groundwater appear to be declining; therefore, it is not expected that the risk will increase over time. (The modeled concentrations show a slight potential future increase in the concentrations in two of the wells of concern.) The maximum concentration measured at the POC was 0.099 mg L⁻¹ in 2015. The HQ is directly proportional to the concentration in water. Therefore, the HQ at the maximum measured concentration is as follows:

$$\text{HQ} = \text{HQ at } 0.021 \text{ mg L}^{-1} * 0.099 \text{ mg L}^{-1} / 0.021 \text{ mg L}^{-1}$$

$$\text{HQ at } 0.021 \text{ mg L}^{-1} = 0.038$$

$$\text{HQ at } 0.099 \text{ mg L}^{-1} = 0.038 * 0.099 \text{ mg L}^{-1} / 0.021 \text{ mg L}^{-1} = 0.17$$

4 As Low As Reasonably Achievable (ALARA) Analysis

Groundwater contamination in well fields associated with in situ uranium recovery operations can be mitigated by replacing pore water. Based on information from Smith Ranch, only header houses 1-1 and 1-2 required further treatment. The dissolved uranium concentrations in the B wells located in header houses 1-1 and 1-2 are given in Table 6. The inter-well median concentration is 0.63 mg L⁻¹.

Table 6 Uranium concentration in header house 1-1 and 1-2 B wells.

Well	Dissolved U-nat concentration (mg L ⁻¹)
B1	0.0829
B2	0.852
B3	0.901
B4	4.65
B5	0.399
B6	0.361
B15	0.108
B16	0.997

Geochemical modeling indicates that each pore volume removes from 2% to 9% of the sorbed uranium. (Enchemica 2017). Assuming the maximum removal of the sorbed uranium at 9% with one pore volume, the reduction in concentration of uranium in the groundwater after stability is re-established, assuming the same geochemical conditions apply, would be reduced by 9%, or 0.057 mg/L. The cost of reduction in groundwater concentration by 0.057 mg L⁻¹ would be equal to the cost per combined pore volume for the two header houses, estimated to be \$31,500.

As noted in the above dose assessment, the only reasonable pathway for exposure to the uranium in groundwater from a well installed in the well field is ingestion of beef consuming impacted water. The calculated dose at the median concentration from Well B4, 3.32 mg L⁻¹ is 1.1 mrem y⁻¹. The dose is directly proportional to the uranium concentration in the groundwater. Therefore, the radiation dose to a single individual averted by treatment with one pore volume would be as follows:

$$\text{Dose averted} = (0.057 \text{ mg L}^{-1})(1.1 \text{ mrem y}^{-1}) / (3.32 \text{ mg L}^{-1}) = 0.019 \text{ mrem y}^{-1}$$

Assuming 100 individuals consume the beef watered from the impacted groundwater each year for 1,000 years, the collective dose averted would be 1.9 person-rem. The cost per person-rem averted by treatment with one pore volume would be as follows:

$$\text{Cost per person-rem averted} = \$31,500 / 1.9 \text{ person-rem} = \$17,000$$

This calculation assumes that the sorbed uranium is reduced by the maximum factor of 9% by treatment with a single pore volume. It is unlikely that additional pore volumes would scale down the uranium concentration in a linear fashion. It would probably be logarithmic. Thus, the reduction in uranium concentration would be less with each pore volume removed (Clay, 2017). In addition, reducing the current uranium concentration would have little impact on the future concentration because the mass of sorbed uranium that is tenuously held to the solids in the aquifer is much greater than the mass of uranium dissolved in the water.

Remediation of conventional uranium recovery facilities, e.g., soil excavation or building decontamination, involves removing the source. In contrast, for *in situ* recovery facilities, decreasing the concentration in the groundwater at the time of site remediation does not necessarily remove the source, which will again impact the groundwater in time via natural processes. For that reason, the ALARA analysis methodology used for

conventional uranium recovery facilities would not seem to be applicable to *in situ* facilities.

5 Environmental Exposure Potential

Eastern Wyoming is largely constituted by prairie grasslands have among the warmest and longest growing seasons of Wyoming's habitat types, as well as relatively deep and well-developed soils. Their location in eastern Wyoming allows them to receive relatively high summer precipitation, ultimately derived from weather systems originating in the Gulf of Mexico which are blocked by the mountains from the basins of western Wyoming. These factors result in grasslands having high primary productivity when compared to other Wyoming habitat types. (WGFD, 2017)

Most of Wyoming's grasslands are classified as either short grass prairie or mixed-grass prairie. Short grass prairie occurs mainly in the southeast corner of the state and extends south into Colorado. Buffalo grass and blue grama grass are the two predominant grass species in short grass prairie. Mixed-grass prairie is common across much of eastern Wyoming. It typically receives more moisture and has greater plant species diversity than short grass prairie. Common mixed-grass prairie plant species include needle-and-thread, western wheatgrass, blue grama, Sandberg's bluegrass, prairie June grass, upland sedges, and Indian rice grass (Knight 1994).

Multiple small mammals reside in the grasslands including shrews, jackrabbits, ground squirrels, prairie dogs, pocket gophers, kangaroo rats, harvest mice, coyotes, foxes, raccoons, skunks, mountain lions, bobcat, elk, mule deer and pronghorn. (WGFD 2016).

For the point of compliance, the only plausible scenario for environmental exposure is represented by a stock tank containing water pumped from the restored ore zone. In that scenario, native animals from the area would be able to drink the water, thereby receiving a dose from the constituents of concern. Potential impacts are described below.

5.1.1 Uranium

To assess potential impacts to wildlife from consumption of water from the restored zone, the RESRAD-BIOTA code was used (ISCORS, 2004). RESRAD-BIOTA is a computer code that implements DOE's Graded Approach methodology described in DOE Technical Standard DOE-STD-1153-2002. RESRAD-BIOTA analyses radiation exposures to biota in either a terrestrial or aquatic system. Radiation exposures are considered to result from contaminated soil, water and sediment, which subsequently result in contamination in air and in different food sources.

The code was developed to coincide with the thinking in proposed 10 CFR 834, Subpart F (1995 - 1996) that was not enacted but which represents DOE's thinking with regard to limits of 0.1 rad day⁻¹ for terrestrial animals and plants. This in in keeping with ICRP thinking that if humans are protected, then biota are protected.

RESRAD-BIOTA was run in general screening mode for this exposure scenario. The most likely organisms to drink from the stock tank are mule deer, pronghorn antelope

and, perhaps, a few other small mammals such as raccoons. The water concentration in the stock tank was set equal to the highest average uranium concentration in well B-004 over the previous three years, 3.77 mg L⁻¹. It was assumed that the three major natural isotopes of uranium, U-234, U-235 and U-238 were in equilibrium.

The code was run in general screening mode, or Level 1, for terrestrial animals. The Biota Concentration Guide (BCG) represents the concentration in an environmental media, in this case water, that result in the 0.1 rad day⁻¹ limit. For the well water assumed to be in the stock tank, the ratio of impact to the animal and the BCG was 6.31E-4 or less than 1% of the limit that might cause concern. This result indicates that drinking of well water containing the modeled concentrations of uranium would result in no detriment to the wildlife.

5.1.2 Arsenic

Reports on effects of arsenic on wildlife are few. However, the Department of Energy's Environmental Management program sponsored work on wildlife resident at the defunct K-25 gaseous diffusion plant site during actions to decommission the site. The 1996 report on toxicity to site wildlife (Sample, et al., 1996) contains helpful information.

As stated in Sample et al. (1996)

The toxicity of inorganic compounds containing arsenic depends on the valence or oxidation state of the arsenic as well as on the physical and chemical properties of the compound in which it occurs. Trivalent (As⁺³) compounds such as arsenic trioxide (As₂O₃), arsenic trisulfide (As₂S₃), and sodium arsenite (NaAsO₂), are generally more toxic than pentavalent (As⁺⁵) compounds such as arsenic pentoxide (As₂O₅), sodium arsenate (Na₂HAsO₄), and calcium arsenate [Ca₃(AsO₄)₂]. The relative toxicity of the trivalent and pentavalent forms may also be affected by factors such as water solubility; the more toxic compounds are generally more water soluble. In this analysis, the effects of the trivalent form of arsenic in water soluble inorganic compounds will be evaluated. In many cases, only total arsenic concentrations are reported so the assessor must assume conservatively that it is all trivalent.

The only wildlife toxicity information readily available for trivalent inorganic arsenic compounds pertains to acute exposures (Sample et al. 1996). For whitetail deer, the estimated lethal dose is 34 mg sodium arsenite/kg or 19.5 mg arsenic/kg (NAS 1977). White tail deer do not reside in the vicinity of Smith Ranch, but both mule deer and pronghorn antelope may be in the area. Assuming the same level of toxicity for a mule deer with a weight of 60 kg, and a median concentration of 0.0275 mg L⁻¹ in well water, the deer would need to consume 4.3E4 L of water in a single day to receive an acute dose.

5.1.3 Selenium

Most published studies of selenium in water and its impacts on wildlife have been confined to situations of irrigation or mine drainage into a wetlands or reservoir and the subsequent toxicity produced by bioaccumulation in the aquatic food chain. In such situations, selenium has been found to be potentially highly toxic to aquatic organisms in concentrations of 2 ppb in water. Further, because of bioaccumulation in the aquatic food chain, it may also be toxic to wildlife that consume aquatic organisms that survive in

water containing selenium. (Lemly, 1997). However, for this document no studies were found that are analogous of the situation at hand; namely, drinking from a stock tank fed from an impacted aquifer.

In “Overview of Selenium Toxicosis”

(<http://www.merckvetmanual.com/toxicology/selenium-toxicosis/overview-of-selenium-toxicosis>). Dr. Jeffery Hall, notes that “selenium is an essential element that has a narrow margin of safety, with the difference between adequate and potentially toxic concentrations in the diet being approximately 10- to 20-fold.” The author notes that selenium concentrations that would be tolerable in livestock feed is in the range of 2 – 5 ppm. (<http://www.merckvetmanual.com/toxicology/selenium-toxicosis/overview-of-selenium-toxicosis>). It is important to note that the mentioned concentrations are in livestock feed, not water. In the referenced overview, concentrations in water are not mentioned, most likely because the bioaccumulation of selenium in plants is what creates a concentration high enough to present toxicity issues.

6 Conclusion

The potential dose to an individual consuming water or using for agricultural purposes at the POE is negligible as geochemical modeling indicates no increase in concentrations of the COCs over background levels within the 1,000-year prescribed follow-up period. Therefore, the current and future modeled concentrations for uranium, arsenic and selenium are As Low As Reasonably Achievable.

The potential adverse health effects were calculated for the current and future modeled concentrations of the COCs at the point of compliance, i.e., the MU-1 itself. It was assumed that the only complete exposure pathway would be consumption of beef ingesting groundwater from the mine unit. The calculated radiation dose for an individual eating beef watered using Mine Unit 1 groundwater at the current median uranium concentration in B-004 is 1.2 mrem y^{-1} . The calculated total cancer risk from uranium and arsenic is less than 1 E-4, thus is within the acceptable range of 1E-6 to 1 E-4. The HQ is 1.4, primarily due to uranium. The potential HQ for selenium at the maximum measured concentration 0.099 mg L^{-1} , is 0.17; at the proposed ACL of 0.20 mg L^{-1} the HQ would be 0.36. A HQ greater than 1.0 does not necessarily indicate a health risk. The HQs are calculated based on the ratio of the average daily intake to a reference dose (RfD). The RfD includes an uncertainty factor of 10 to 1,000. The RfD for uranium, 0.0002 mg $L^{-1} d^{-1}$, was derived using an uncertainty factor of 300 (Stalcup, D. 2016). In addition, the dose and risks were calculated assuming an individual obtains all of his or her meat from local beef. Therefore, it is unlikely that any adverse health effect would be incurred from eating beef watered with Mine Unit 1 groundwater.

The calculated dose and risk from uranium at the maximum, modeled future concentration is 8.9 mrem y^{-1} . The cancer risk from uranium was calculated to be 8.9 E-5, less than the acceptable risk of 1 E-4. The cancer risk from arsenic was calculated to be 1.1 E-4. The cancer risks from arsenic and uranium were not summed since the maximum concentration is predicted to occur at different times. Selenium is not a known carcinogen. As with the risks from current concentrations, the intake was calculated assuming the individual consumed only the local beef. The risks are acceptable. The HQ for uranium was 8.9; however, as noted above, the RfD includes an uncertainty

factor of 300. Therefore, it is unlikely that consumption of beef watered from a well in Mine Unit 1 would result in adverse health effects.

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