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Dose Assessment Modeling for the WCS Site Model v0.205

20 November 2013

Prepared for Waste Control Specialists, LLC, by

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1.0 Overview

At its disposal site in Andrews County, Texas, Waste Control Specialists, LLC, (WCS) has constructed two disposal units for low-level radioactive waste (LLW). One is the Compact Waste Disposal Facility (CWF) for disposal of LLW generated in states within the Texas Compact and other generators in other states with approval. The other is a Federal Facility Waste Disposal Facility (FWF) for disposal of LLW that is the responsibility of the federal government. Performance objectives for land disposal of radioactive waste are used to assess whether these disposal units and containment technologies are protective of human health. These objectives are described in regulations developed by the Texas Commission on Environmental Quality (TCEQ), and are encoded in the Texas Administrative Code (TAC) Title 30 Chapter 336 *Radioactive Substance Rules* (TAC, 2004), and the Texas Health and Safety Code (THSC) Title 5 Subtitle D *Texas Radiation Control Act* (THSC, 2011). These regulations are compatible with Title 10 Code of Federal Regulations Part 61 (10 CFR 61) Subpart C *Licensing Requirements for Land Disposal of Radioactive Waste*, promulgated by the U.S. Nuclear Regulatory Commission (NRC). Texas, as an NRC Agreement State, has direct authority over licensing of the facility.

In 2007, WCS submitted their *Application for License to Authorize Near-Surface Land Disposal of Low-Level Radioactive Waste* (WCS, 2007) to the TCEQ, and in April of 2012, WCS began disposal activities. A Performance Assessment (PA) of the disposal facility was included as a component of the license application in order to full requirements under Subchapter H of TAC Title 30 Chapter 336 (TAC, 2004) to provide sufficient technical and environmental analyses to demonstrate that the facility will meet the applicable performance objectives. The refinement of this initial PA to address site-specific exposure pathways and scenarios in a probabilistic manner is the subject of this paper.

The computer model supporting the PA is a mathematical implementation of the conceptual site model (CSM) and has two major components. The first component is contaminant transport, an evaluation of the release over time of radionuclides from disposed wastes, their migration through engineered and natural materials, and their occurrence in environmental media (primarily vadose and surface soils). The second component is dose assessment, which includes models of future human activities and behaviors, and calculation of radiation dose for all relevant exposure scenarios and pathways. This paper describes the assumptions, inputs, and methods related to the dose assessment. The CSM underlying the dose assessment is described in *Conceptual Site Model for Low-Level Radioactive Waste Disposal at the WCS Andrews Facility*.

Radiation dose limits for the general public in relation to licensing of near-surface land disposal of LLW are defined in TAC Title 30 Chapter 336 Rule §336.724. The Chapter 336 regulations (Rule §336.725) also specify that "design, operation, and closure of the land disposal facility shall ensure protection of any individual inadvertently intruding into the disposal site and occupying the site or contacting the waste at any time after loss of active institutional controls over the disposal site are removed." Insofar as inadvertent intrusion encompasses exposure of individuals who engage in activities without knowledge of the disposal units or intent to deliberately exhume waste, no practical distinction between the general public and inadvertent intruders is made in the dose assessment calculations.

2.0 Parameter Values Summary

Individual model parameters and associated input values used in the dose assessment component of the WCS Site Model are identified in the *WCS Site Model Parameters.pdf*. In this summary, a more comprehensive record for each parameter is provided, including the source of the values and notes explaining the basis. The model has been developed as a probabilistic model taking into account site-specific conditions and uncertainties inherent to model parameters. The GoldSim systems analysis software (GTG, 2012) was used to construct the probabilistic PA model.

For distributions, the following notation is used:

- N(μ, σ, [*min*, *max*]) represents a normal distribution with mean μ and standard deviation σ, and optional truncation at the specified *min*imum and *max*imum,
- LN(*GM*, *GSD*, [*min*, *max*]) represents a log-normal distribution with geometric mean GM and geometric standard deviation GSD, and optional truncation points *min* and *max*,
- U(*min*, *max*) represents a uniform distribution with lower bound *min* and upper bound *max*,
- Beta(μ, σ, *min*, *max*) represents a generalized beta distribution with mean μ, standard deviation σ, minimum *min*, and maximum *max*,
- Gamma(μ, σ) represents a gamma distribution with mean μ and standard deviation σ, and
- TRI(*min*, *m*, *max*) represents a triangular distribution with lower bound *min*, mode *m*, and upper bound *max*.

The term ‘Small’ used in some distributions refers to a very small, positive value. The term ‘Large’ used in some distributions refers to a very large, positive value.

Table 1. Parameter Values Summary for Dose Conversion Factors

Parameter	Units	Point Estimate	Distribution	Source	Notes
Dose conversion factors; ingestion	Sv/Bq	See Excel workbook *WCS Site Model Parameters.xlsx*	—	ICRP 1996, Table A.1; FGR 11, Table 2.1	User-selected source
Dose conversion factors; inhalation	Sv/Bq	See *WCS Site Model Parameters.xlsx*	—	ICRP 1996, Tables A.2 and A.3; FGR 11, Table 2.2	User-selected source. Separate values for inert gases.
Dose conversion factors; external, soil	$Sv/Bq \cdot s \cdot m^{-3}$	See *WCS Site Model Parameters.xlsx*	—	EPA 1999; electronic database, Table F12TIII7	Infinite soil source; FGR 12. Incorporates ICRP 60 tissue weighting factors.
External dose conversion factors; modifying factors	unitless	See *calculation sheet WCS014*	See WCS014	See WCS014	Used in conjunction with the infinite-source external DCFs to apply the DCFs to less-than-infinite geometries.

Parameter	Units	Point Estimate	Distribution	Source	Notes
Radon-222 inhalation dose conversion factor	$Sv/Bq \cdot hr \cdot m^{-3}$	7.85E-9	—	See WCS015	Calculated from a value of 5 mSv/working level month; progeny at full equilibrium.
Argon-39 inhalation dose conversion factor	$Sv/Bq \cdot d \cdot m^{-3}$	1.1E-11	—	ICRP 1996, Table A.4	
Krypton-85 inhalation dose conversion factor	$Sv/Bq \cdot d \cdot m^{-3}$	2.2E-11	—	ICRP 1996, Table A.4	
Inhalation rate; noble gases	m^3/yr	8400	(discrete)	WCS, 2007 (Table 8.0-6.3-1)	**Placeholder.** For a standard worker.
Radon-222 indoor progeny equilibrium factor	unitless	0.4	(discrete)	See WCS015	**Placeholder.**
Air transit time; residence	min	27	(discrete)	EPA, 2012	**Placeholder.** Based on an air exchange rate of 0.45/hr.

Table 2. Parameter Values Summary for Calculation of Scenario Probabilities

Parameter	Units	Point Estimate	Distribution	Source	Notes
On-Site Residence and Home Garden					
Home siting rate	yr^{-1}	0.02	N(0.02, 0.001, 0, Large)	—	**Placeholder.** Based on two homes built in the past 100 years.
Home siting area	mi^2	16	U(9, 23)	—	**Placeholder.** Range based on a 1-mile wide strip along the 4.5-mi stretch of Highway 176, up to the entire 23 mi^2 WCS site.
Surface dispersion area for air rotary cuttings (CWF)	m^2	150	U(150, 20127)	—	**Placeholder.** Range based on area of a home garden and the area of the CWF disposal unit.
Surface dispersion area for air rotary cuttings (FWF)	m^2	150	U(150, 154998)	—	**Placeholder.** Range based on area of a home garden and the area of the FWF disposal unit.
Oil Well Location and Borehole Cuttings Activities					
Oil well borehole diameter	inches	14	U(11, 17.5)	http://permianbasin360.com/fulltext/?nxd_id=107037 Accessed April 28, 2011	**Placeholder.** Quoted from a Henry Resources LLC employee, in reference to surface casing.
Area in which oil wells are sited	ha	1960	—	WCS, 2007; Volume 16	Based on a survey finding 5 wells within a 2.5-km radius of the disposal facilities.
Number of oil wells sited	—	5	—	WCS, 2007; Volume 16	Based on a survey finding 5 wells within a 2.5-km radius of the disposal facilities.

Parameter	Units	Point Estimate	Distribution	Source	Notes
Oil well development period	yr	62.5	U(25, 100)	—	**Placeholder.** Period of time to which surveyed wells sited near facility were assigned.

Table 3. Parameter Values Summary for Calculation of Exposure Concentrations

Parameter	Units	Point Estimate	Distribution	Source	Notes
Oil field worker exposure area	m^2	150	—	—	Exposure area for drill crew and, if air rotary is selected, area in which cuttings are initially dispersed. External DCF for oil field worker based on this value.
Garden exposure area, On-Site Resident	m^2	150	—	—	Exposure area for garden activities. Upper-bound external DCF for garden exposure based on this value.
Ranching exposure area	mi^2	154	TRI(15, 150, 300)	Personal interviews	**Placeholder.** County extension agent estimated most Andrews Cty ranches were between 125 to 250 mi^2. Minimum based on ranch size of an interviewee ("one of the smallest in the area").
Farming exposure area	ha	1153	U(200, 5500)	Smith et al, 1985	**Placeholder.** Approximate range of farm sizes described for cotton farming on the Texas southern high plains.
Soil gas : indoor air ratio (alpha, residential)	—	0.0088	LN(0.0092, 0.05, 2.5E-5, 0.94)	EPA, 2012, Table 12; Figure 27	Table 12 provides descriptive statistics related to the data in Figure 27, including the mean (0.0092) and standard deviation (0.05). That the mean is about a factor of three larger than the median indicates a skewed distribution. Minima and maxima are 2.5E-05 and 0.94, respectively.
Produce : soil concentration ratios	Bq/g dry plant per Bq/g soil	See *WCS Site Model Parameters.xlsx*	See *Biological Modeling* white paper	NRC (1992) (Table 6.16)	**Placeholder.** Based on values for fruits used as the geometric mean of a lognormal distribution. See *Biological Modeling* white paper
Dry to wet conversion factor; produce	g dry plant per g wet plant	0.25	N(0.25, 0.025, Small, 1-Small)	NRC (1992) (Table 6.17)	**Placeholder.** For nonleafy vegetables.
Grain : soil concentration ratios	Bq/g dry plant per Bq/g soil	See *WCS Site Model Parameters.xlsx*	See *Biological Modeling* white paper	NRC (1992) (Table 6.16)	**Placeholder.** Based on values for grains used as the geometric mean of a lognormal distribution. See *Biological Modeling* white paper

Parameter	Units	Point Estimate	Distribution	Source	Notes
Dry to wet conversion factor; grain	g dry plant per g wet plant	0.91	N(0.91, 0.02, Small, 1-Small)	NRC (1992) (Table 6.17)	**Placeholder.**
Forage : soil concentration ratios	Bq/g dry plant per Bq/g soil	See *WCS Site Model Parameters.xlsx*	See *Biological Modeling* white paper	NRC (1992) (Table 6.16)	**Placeholder.** Based on values for leafy vegetation used as the geometric mean of a lognormal distribution. See *Biological Modeling* white paper
Dry to wet conversion factor; forage	g dry plant per g wet plant	0.22	N(0.22, 0.022, Small, 1-Small)	NRC (1992) (Table 6.17)	**Placeholder.**
Feed : beef transfer factors	Bq/g per Bq/d	See *WCS Site Model Parameters.xlsx*	—	NRC (1992) (Table 6.18)	Distribution development pending.
Feed : game meat transfer factors	Bq/g per Bq/d	See *WCS Site Model Parameters.xlsx*	—	NRC (1992) (Table 6.18)	Distribution development pending.
Forage ingestion rate; cattle	kg wet weight/day	27	N(27, 1, Small, Large)	NRC (1992) (Table 6.8)	**Placeholder.**
Soil ingestion fraction; cattle	—	0.05	N(0.05, 0.005, Small, 1-Small)	NRC (1992) (Table 6.5.1)	**Placeholder.** Fraction of dry matter intake that is soil.
Mule deer body weight	kg	59.2	N(59.2, 2.3, Small, Large)	Relyea et al, 2000	**Placeholder.** Assumed distributional form.
Forage ingestion rate; mule deer	kg wet weight/day	7.7	—	EPA, 1993; Equation 3-9	Calculated as (0.577 × (BW × 1000 g/kg)^0.727) / forage dry-wet conversion factor.
Soil ingestion fraction; mule deer	—	0.05	N(0.05, 0.005, Small, 1-Small)	NRC (1992) (Table 6.5.1)	**Placeholder.** Fraction of dry matter intake that is soil. Value for cattle used as a surrogate.
Home range; mule deer	ha	1375	N(1375, 200, Small, Large)	Relyea et al, 2000	**Placeholder.** Assumed distributional form.
Tritium and Carbon-14 Biota Concentrations					
Tritium specific activity equivalence	Bq H3/g plant H per Bq H3/g soil H_2O H	1.0	—	NRC (1992) Appendix D	Tritium activity in plants is assumed to be equivalent to activity in the contaminating medium.
Water to H conversion	g H_2O/ g H	9.0	—	NRC (1992) Equation D.1.	
Fraction H in produce	g H / g wet weight plant	0.1	N(0.1, 0.01, Small, 1-Small)	NRC (1992) Table D.1.	**Placeholder.**
Soil water content	g soil H_2O / g dry soil	0.1	N(0.1, 0.01, Small, 1-Small)	NRC (1992) Table D.1.	**Placeholder.**

Parameter	Units	Point Estimate	Distribution	Source	Notes
Carbon concentration factor; produce	g dry plant per g wet plant	0.7	N(0.7, 0.01, Small, Large)	NRC (1992) Appendix C	**Placeholder.** Assumed to be dry weight.
Fraction H in forage	g H / g wet weight plant	0.1	N(0.1, 0.01, Small, 1-Small)	NRC (1992) Table D.1.	**Placeholder.**
Water ingestion rate; mule deer	L/day	1.9	—	EPA, 1993; Equation 3-17	Calculated as (0.099 × (BW × 1000 g/kg)^0.727) / water density.
Fraction C in forage	g H / g wet weight plant	0.09	N(0.09, 0.01, Small, 1-Small)	NRC (1992) Table C.1.	**Placeholder.**

Table 4. Parameter Values Summary for Receptor Exposure Characteristics

Parameter	Units	Point Estimate	Distribution	Source	Notes
Soil ingestion rate	mg/day	50	N(50, 1, Small, Large)	NRC (1992) Section 6.2.1	**Placeholder.** To be replaced with distribution based on data cited in Exposure Factors Handbook (EPA, 2011).
Vegetable ingestion rate	kg/yr	108	N(62, 10, Small, Large)	NRC (1992) Table 6.15	**Placeholder.** Leafy and other vegetables. To be replaced with distribution based on data cited in Exposure Factors Handbook (EPA, 2011).
Fruit ingestion rate	kg/yr	108	N(46, 10, Small, Large)	NRC (1992) Table 6.15	**Placeholder.** To be replaced with distribution based on data cited in Exposure Factors Handbook (EPA, 2011).
Grain ingestion rate	kg/yr	69	N(69, 7, Small, Large)	NRC (1992) Table 6.15	**Placeholder.** To be replaced with distribution based on data cited in Exposure Factors Handbook (EPA, 2011).
Beef ingestion rate	kg/yr	59	N(59, 10, Small, Large)	NRC (1992) Table 6.15	**Placeholder.** To be replaced with distribution based on data cited in Exposure Factors Handbook (EPA, 2011).
Game meat ingestion rate	kg/yr	59	N(59, 10, Small, Large)	beef used as a surrogate	**Placeholder.** To be replaced with distribution based on data cited in Exposure Factors Handbook (EPA, 2011).
Inhalation rate; general	m^3/hr	1.2	N(1.2, 0.001, Small, Large)	NRC (1992) Table 6.23	**Placeholder.** To be replaced with distribution based on data cited in Exposure Factors Handbook (EPA, 2011).
Inhalation rate; moderate	m^3/hr	1.2	N(1.2, 0.001, Small, Large)	NRC (1992) Table 6.23	**Placeholder.** To be replaced with distribution based on data cited in Exposure Factors Handbook (EPA, 2011).
Time fraction; resident	—	0.958 (8400 hr/yr)	N(8400, 100, 8000, 8766)	EPA, 1991	**Placeholder.** The total time at a residence. Assumes 350 d/yr at the residence.

Parameter	Units	Point Estimate	Distribution	Source	Notes
Time fraction; resident (outdoors)	—	0.034 (300 hr/yr)	N(300, 30, 190, 410)	—	**Placeholder.** Truncated at the 0.01 and 99.99 percentiles of the distribution.
Garden time; resident (outdoors in garden)	—	0.5	TRI(0.25, 0.5, 0.75)	—	**Placeholder.** Applied as a multiplier to the outdoor time.
Time fraction; resident (indoors)	—	—	—	—	Calculated as total time at the residence minus outdoor time at the residence.
Time fraction; boundary individual	—	0.083 (730 hr/yr)	N(730, 1, Small, 1-Small)	WCS, 2007; Table 8.0-6.3-1	**Placeholder.**
Time fraction; maintenance worker	—	0.011 (96 hr/yr)	N(96, 1, Small, 1-Small)	WCS, 2007; Table 8.0-6.3-1	**Placeholder.**
Time fraction; oil field worker	—	0.011 (96 hr/yr)	N(96, 1, Small, 1-Small)	Maintenance worker used as surrogate.	**Placeholder.**
Time fraction; rancher	—	0.119 (1040 hr/yr)	N(1040, 80, Small, 1-Small)	—	**Placeholder.** Assumes 130 d/yr, 8 hr/d.
Time fraction; hunter	—	0.0046 (40 hr/yr)	N(40, 80, Small, 1-Small)	—	**Placeholder.** Assumes 5 d/yr, 8 hr/d.
Time fraction; farmer	—	0.027 (240 hr/yr)	N(240, 20, Small, 1-Small)	—	**Placeholder.** Assumes 30 d/yr, 8 hr/d.
Mud pit area; oil well	m^2	150	—	—	Used to calculate exposure time fractions above the mud pit for various receptors.
Yard area; on-site resident	ac (and m^2)	0.25	N(0.25, 0.025, 400 m^2, 1600 m^2)	—	**Placeholder.** Area around home where most outdoor activity occurs.
Gamma attenuation factor; indoors	—	0.4	N(0.4, 0.04, Small, 1)	EPA, 2000	**Placeholder.**

3.0 Land Use Scenarios and Pathways

A summary of all receptor scenarios and associated exposure pathways is provided in Figure 1. The individual scenarios are described in the subsections below.

Exposure Pathways

Receptor	Ingestion: produce or grain[1]	Ingestion: beef or game[2]	Ingestion: soil	Inhalation: indoor air	Inhalation: outdoor air	External Irradiation
On-Site Resident	●		●	●	●	●
Eunice Resident					●	
Adjacent Resident					●	
Ranch Worker		●	●		●	●
Oilfield Worker			●		●	●
Recreational Hunter		●	●		●	●
Dry Land Farmer	●		●		●	●
Maintenance Worker[3]			●		●	●
Boundary Individual[3]					●	

● These exposure pathways are potentially complete and may result in radiation dose.

[1] Residents consume garden produce; the dry land farmer consumes grain.
[2] The ranch worker consumes beef; the hunter consumes game (deer).
[3] Present only during the institutional control period.

Figure 1. Receptor Exposure Scenarios and Pathways.

3.1 Elimination of Water-Related Exposure Pathways

3.1.1 Summary of Rationale

The dose assessment calculations supporting the license application (WCS, 2007) included an evaluation of dose for drinking water, beef, and milk exposures to a "site boundary individual" and an "inadvertent intruder resident" related to use of contaminated well water from the 225-ft sandstone, assuming that it could provide a sufficient water supply. As detailed below, exposure pathways for future receptors related to use of well water are incomplete due to the effectively zero joint probability of a driller completing a borehole within the 225-ft sandstone, and then developing, operating, and maintaining a very-low-producing well in this stratum.

Information related to land use, domestic water use, and water well drilling was gathered from online resources and from personal interviews conducted during a site visit in September, 2012. Water perched on top of "red bed" clays (e.g., water found within the Ogallala-Antlers-Gatuña (OAG) aquifer) is the only source of potable groundwater recognized by the well drillers, well service professionals, and resident-ranchers interviewed. This information, coupled with information from water delivery businesses that the minimum rate of domestic water use for residents far exceeds the potential yield of a well in the 225-ft zone (estimated at less than

1 L/day), supports a conclusion that there are no potentially complete residential exposure pathways for domestic water derived from the 225-ft sandstone. Furthermore, interviewees stated that drillers use the presence of red bed clay in drill cuttings as an indication that the zone where OAG water may exist has been drilled through. For this reason, drillers seeking OAG groundwater would not drill through the 7-m thick red bed clay layer in the upper fill zone of the cover after failing to find groundwater in the 2-m thick evapotranspiration and bio-barrier surface layers. Water well driller and residential exposure pathways related to drill cuttings for a water well are therefore also incomplete. The scenario of using groundwater from the 225-ft sandstone for domestic water supply is therefore not credible.

3.1.2 Assumptions

It is assumed that knowledge of regional groundwater conditions persists throughout the modeling period based on continuation of present-day land use, including the existence of the communities of Andrews, TX and Eunice, NM with rural residences and ranches outside the municipal areas. This knowledge extends to the potential availability of shallow OAG groundwater, and deeper but non-potable groundwater in the Santa Rosa Formation of the Dockum Group. The present-day validity of assuming this knowledge of groundwater conditions was confirmed in discussions with three regional water drillers and well service professionals, as well as ranchers in western Andrews County, TX.

3.1.3 Detailed Basis for Elimination of Water Well Exposure Pathways

Exposure pathways related to drilling a water well through the wastes are incomplete and not credible because:

1. Water perched on top of “red bed” clays (water found within the OAG) is the only source of potable groundwater available for residential use in northwestern Andrews County, as recognized by the three water well drillers / well service professionals interviewed. (A groundwater is defined as a saturated geologic formation, group of formations, or part of a formation which has a hydraulic conductivity equal to or greater than 1×10^{-5} cm/s in 30 TAC 350.4.) These individuals indicated that drillers use the presence of red bed clay in cuttings as an indication that the zone where OAG water may exist has been drilled through. Therefore, drillers who by chance have spudded a borehole over the waste footprint will encounter the approximately 7-m thick clay layer in the upper red bed fill zone of the cover (beneath the evapotranspiration and bio-barrier layers), and will not continue drilling if they are seeking potable OAG water. Further, the location of the waste disposal facilities on a ridge of red bed that is near the ground surface should be an indication to drillers that they are unlikely to encounter perched OAG water there and is therefore a deterrent to drilling at this location. Since dry holes in the intact OAG in western Andrews County are not uncommon according to interviewees, the driller is likely to simply move to a nearby location in search of a productive well. Interviewees report that drillers routinely need to drill several boreholes before finding groundwater of sufficient yield to warrant installation of a well.

2. Residents who ranch would be highly unlikely to drill to the Santa Rosa for stock water because it is economically infeasible. A driller with experience in drilling to this depth indicated an approximate cost of $100,000 or more for such a well. Santa Rosa groundwater has levels of total dissolved solids of about 3,000 mg/L (Appendix 2.6.2 in WCS 2007), which is considered satisfactory for cattle but which may cause temporary and mild diarrhea in humans (National Research Council, 1974). If less-saline OAG water were available for stock it would be preferred. Therefore, based on considerations of economic infeasibility and water quality, there is judged to be effectively no potential for exposure to cuttings related to drilling to the Santa Rosa for stock water.

In the hypothetical event of a water well reaching the 225-ft sandstone, the potential yield is far below a minimum residential water demand because:

3. No domestic wells with a well yield below 0.25 gpm (1360 L/d) within Andrews County are recorded in databases maintained by the Texas Water Development Board (TWDB): http://wiid.twdb.texas.gov/help/waterWellMapper.htm, or by the TCEQ: http://www.tceq.texas.gov/gis/waterwellview.html .

4. The national Water Systems Council recommends a minimum yield of 1 gpm (5450 L/d) in order to develop a domestic well. A telephone survey of three Midland-Odessa drilling companies indicates that these companies agree with this recommendation and follow this practice.

5. In-person interviews of three well drillers / well service professionals indicated they consider minimum acceptable well yields for Andrews County to be 2, 2 to 2.5, and 10 gpm (about 10,000, 10,000 to 14,000, and 55,000 L/d) respectively. Ranchers indicated a minimum well yield of 1 gpm (5450 L/d), below which they would try to drill in another location. One rancher said he might consider a minimum yield of ½ gpm (2725 L/d) if that were the best achievable after several attempts.

6. In-person interviews of three well drillers / well service professionals indicated they would not recognize a saturated zone with a potential well yield of 0.4 L/d (7E-5 gpm) as a possible source of water.

7. The 225-ft sandstone estimated yield of 0.4 L/d (0.1 gal/d, or gpd) represents only 0.04% of the per capita 250 gal/d (950 L/d) water demand in Andrews County (FIPS code 003) described in a USGS database (http://water.usgs.gov/watuse/data/2005/). Telephone interviews with three water trucking services in Decatur, Midland, and El Paso, TX indicated that residential customers paying for trucked water used a minimum of 50 gpd (190 L/d), and perhaps more than 300 gpd (1100 L/d). The 50 gpd value typically represents a household of one individual who practices water conservation. Even if a household used only 50 gpd (190 L/d), there is no economic value in installing and maintaining a system to recover an additional 0.1 gpd (0.4 L/d).

8. The saturated hydraulic conductivity of the 225-ft sandstone is about 9×10^{-9} cm/s (see the *Groundwater Modeling* white paper), which is far below the minimum value of 1×10^{-5} cm/s at which TCEQ defines a groundwater bearing unit for purposes of aquifer

classification (http://www.tceq.texas.gov/publications/rg/rg-366_trrp_08.html/at_download/file).

3.2 Oil and Gas Development Scenario

The area surrounding the WCS Andrews, TX facility supports oil extraction, and a 2005 survey described in Volume 16 of the License Application (WCS, 2007) identified five oil wells within a 3.2-km (2-mile) radius of the site. Productive oil wells in the larger area surrounding the WCS facility are completed at depths ranging between approximately 1500 and 5000 m (5,000 and 16,000 ft).

An Oil Field Worker may be exposed during an assumed oil development period that occurs at a time following the modeled structural failure of the concrete cap. After the cap structure fails (specifically the reinforced concrete cover), an oil or gas well is assumed to be able to penetrate into the buried wastes. As described in Section 4.1.2, cuttings-related doses for the Oil Field Worker may be evaluated based on the probability that a well will be located above the disposed waste. Alternatively, a model user may evaluate the dose conditional on the assumption that a well is drilled through CWF and FWF wastes. An Oil Field Worker may be exposed via pathways related to:

- outdoor inhalation of gas-phase radionuclides emanating from the closed facilities,
- inhalation of particulates released by wind erosion from surface soil above the facilities,
- inadvertent ingestion of surface soil,
- external dose from surface and near-surface soil, and,
- external dose from oil well drill cuttings in an open mud pit (mud rotary drilling).

The particulate inhalation, inadvertent soil ingestion, and surface soil external dose pathways may include dose from the contribution of oil well drill cuttings mixed into soil (air rotary drilling). As described in Sections 4.1.2 and 4.2, an assumption of either air rotary or mud rotary drilling for a future oil or gas well may be selected by the model user.

Ellenbecker (2012) refers to the recent successful use of air rotary for drilling in the red bed formation of West Texas. There are three items of interest in this article. One is the successful use of air rotary rather than mud rotary for drilling a well through the red bed. A second item of interest is the reference to the practice of pre-setting the surface casing of the well, with subsequent drilling of the oil production well using a different rig:

> "In Texas, the Railroad Commission of Texas sets the depth required for each surface hole, generally 100 feet to 150 feet below the water table. The production oil wells that will be drilled later will be 11,000 feet at total depth." – Ellenbecker (2012)

It would be during this initial drilling and setting of the surface casing for an oil or gas well that the WCS disposal units would be encountered. The use of a different rig for surface and intermediate drilling would be because a smaller rig set up to put casing in place is more efficient than using a single rig for all stages. The rigs may use different equipment and drill fluid ("water, foam, and polymer" described in the article on air rotary drilling through the red bed). The segregation of drilling into surface, intermediate, and final depth components is also described in

a New Mexico state publication for pollution prevention during oil and gas development (http://www.emnrd.state.nm.us/OCD/documents/2000PollutionPreventionBMPs.pdf).

The third item of interest in Ellenbecker (2012) is that use of a mud pit is mentioned as part of the air drilling operation. This suggests that the current assumption in the WCS Site Model v0.205 that cuttings from air rotary drilling are left on the ground surface, is extremely conservative. This assumption will be revisited under PA maintenance, and is likely to be dismissed.

3.3 Residential Scenarios

Residences under present-day conditions in western Andrews County are closely associated with ranching. The far western portion of the county south of Monument Draw, aside from industrial developments such as WCS, is devoted to ranching. Some ranchers reside in town, but all current residences located in this area are associated with ranching. In principle, a composite resident-rancher scenario could therefore be developed. However, in the interest of clarifying the relative risks from multiple hypothetical future land uses and activities, the residential scenarios are kept distinct from ranching and other activity-focused land use scenarios.

There are three types of residential scenario evaluated in the WCS Site Model. These are briefly described below.

The nearest present-day resident, 6 km (4 miles) west of the disposal facilities (WCS 2007) may be exposed at any point during the modeling period, both before and after loss of institutional control. The Nearest Resident may be exposed via pathways related to

- inhalation of gas-phase radionuclides emanating from the closed facilities, and
- inhalation of particulates resuspended from surface soil above the facilities and transported in the atmosphere.

The Adjacent Resident is assumed to be present at a time following the loss of institutional control at a location just outside a 100-m wide buffer zone around the closed facilities. The Adjacent Resident may likewise be exposed to the same pathways:

- inhalation of gas-phase radionuclides emanating from the closed facilities, and
- inhalation of particulates resuspended from surface soil above the facilities and transported in the atmosphere.

The On-Site Resident may be exposed at a time following the loss of institutional control at a location on either the FWF or CWF. As described in Section 4.1.1, doses for the On-Site Resident may be evaluated based on the probability that a home comes to be located above the disposed waste at some point in the future. Alternatively, a model user may evaluate the dose conditional on the assumption that a residence is located above the waste at all times following the loss of institutional control. The On-Site Resident may be exposed via pathways related to

- outdoor inhalation of gas-phase radionuclides emanating from the closed facilities,

- indoor inhalation of gas-phase radionuclides, including radon, infiltrating a residence at the soil interface of the slab or basement floor,
- inhalation of particulates resuspended from surface soil above the facilities,
- inadvertent ingestion of surface soil,
- ingestion of home-raised produce,
- external dose from surface and near-surface soil, and
- external dose from oil well drill cuttings in a closed mud pit (mud rotary drilling only).

The disposition of drill cuttings from a future oil or gas well, dependent upon the assumed drilling methodology, is described in Section 4.2. Dose related to air rotary cuttings (mixed in surface soil) or mud rotary cuttings (in a closed mud pit) is only relevant at model times following structural failure of the cap (see Section 3.2) and under the condition that an oil or gas well has been drilled through the cap.

3.4 Rancher Scenario

As noted in Section 3.3, the far western portion of Andrews County, TX south of Monument Draw is largely devoted to ranching. In discussions with a county agricultural extension agent and ranchers it is evident that ranching in this area is presently overwhelmingly related to beef cattle and further that cattle ranching is exclusively cow-calf operations where calves are raised and weaned on rangeland and then sold.

Cattle in pastures may be exposed to contaminants via direct soil ingestion while grazing and also via ingestion of plants growing in contaminated soil. In a commercial cow-calf ranching operation, where cattle grazed on pasture are sent to animal feeding operations prior to slaughter and the meat distributed commercially, there is little possibility of significant human radionuclide exposure from beef. This is because radionuclide accumulation in muscle and fat tissue while grazing will largely be lost during subsequent time spent being finished in a different setting prior to slaughter. The likelihood that commercial ranchers may obtain beef for personal consumption from their operations is unknown. In order to evaluate the possible significance of this exposure pathway, it is protectively assumed that a Rancher raises some cattle for personal consumption and slaughters the animals immediately after grazing on contaminated pasture.

Rancher interviews were focused on determining water requirements and availability related to current ranching practices. Both ranchers and water well professionals confirmed that stock water is generally obtained from wells completed in the OAG aquifer. Interviewees stated it would be infeasible for a rancher to initiate construction of a stock well in the Santa Rosa formation due to the prohibitive cost of drilling and developing a well at this depth. A complete discussion of the basis for eliminating consideration of water-related exposure pathways is provided in Section 3.1.

The Rancher may be exposed at a time following the loss of institutional control on ranch land encompassing the FWF or CWF facilities. As described in Section 4.3, the Ranching scenario employs area-averaged exposure concentrations within an area that encompasses both disposal units. The Rancher may be exposed via pathways related to

- outdoor inhalation of gas-phase radionuclides emanating from the closed facilities,
- inhalation of particulates resuspended from surface soil above the facilities and transported in the atmosphere,
- inadvertent ingestion of surface soil,
- external dose from surface and near-surface soil,
- external dose from oil well drill cuttings in a closed mud pit (mud rotary drilling only), and
- ingestion of beef from cattle grazed on ranch land encompassing the facilities.

The disposition of drill cuttings from a future oil or gas well, dependent upon the assumed drilling methodology, is described in Section 4.2. Dose related to air rotary cuttings (mixed in surface soil) or mud rotary cuttings (in a closed mud pit) is only relevant at model times following structural failure of the cap (see Section 3.2) and under the condition that an oil or gas well has been drilled through the cap.

3.5 Hunter Scenario

Although the land surrounding the disposal facility is primarily used for cattle grazing, as described in Section 3.4, hunting of game animals is also common on ranch lands in Andrews County. Mule deer, northern bobwhite, scaled quail, collared peccary (javelina), and mourning dove are important game species in the region. Based on an informal survey of online hunting forums, mule deer are assumed to be the primary game species in western Andrews County where the WCS facility is located.

The Hunter may be exposed at a time following the loss of institutional control on ranch land encompassing the FWF or CWF facilities. As described in Section 4.3, the Hunting scenario employs area-averaged exposure concentrations within an area that encompasses both disposal units. The Hunter may be exposed via pathways related to

- outdoor inhalation of gas-phase radionuclides emanating from the closed facilities,
- inhalation of particulates resuspended from surface soil above the facilities and transported in the atmosphere,
- inadvertent ingestion of surface soil,
- external dose from surface and near-surface soil,
- external dose from oil well drill cuttings in a closed mud pit (mud rotary drilling only), and
- ingestion of meat from mule deer grazing on land that encompassing the facilities.

The disposition of drill cuttings from a future oil or gas well, dependent upon the assumed drilling methodology, is described in Section 4.2. Dose related to air rotary cuttings (mixed in surface soil) or mud rotary cuttings (in a closed mud pit) is only relevant at model times following structural failure of the cap (see Section 3.2) and under the condition that an oil or gas well has been drilled through the cap.

3.6 Dry Land Farmer Scenario

The region of Andrews County, TX south of Monument Draw may support marginally productive dry land farming for crops such as cotton, sorghum, and winter wheat. According to a county agricultural extension agent, the dominant agricultural crop (approximately 90%) in unirrigated areas of Andrews County is cotton. Grain sorghum is also grown, and this crop was observed along Route 176 during a site visit in September 2012.

The dry land farming in this area is a commercial activity, and even in the case of edible crops such as sorghum the farming is not associated with crops raised for human consumption. However, in order to evaluate the possible significance of an exposure pathway involving consumption of grains grown by dry land farming, it is protectively assumed that a Farmer raises some grain for personal consumption.

The Farmer may be exposed at a time following the loss of institutional control on ranch land encompassing the FWF or CWF facilities. As described in Section 4.3, the Farming scenario employs area-averaged exposure concentrations within an area that encompasses both disposal units. The Farmer may be exposed via pathways related to

- outdoor inhalation of gas-phase radionuclides emanating from the closed facilities,
- inhalation of particulates resuspended from surface soil above the facilities and transported in the atmosphere,
- inadvertent ingestion of surface soil,
- external dose from surface and near-surface soil,
- external dose from oil well drill cuttings in a closed mud pit (mud rotary drilling only), and
- ingestion of grain grown on farmland encompassing the facilities.

The disposition of drill cuttings from a future oil or gas well, dependent upon the assumed drilling methodology, is described in Section 4.2. Dose related to air rotary cuttings (mixed in surface soil) or mud rotary cuttings (in a closed mud pit) is only relevant at model times following structural failure of the cap (see Section 3.2) and under the condition that an oil or gas well has been drilled through the cap.

3.7 Maintenance Worker and Boundary Individual Scenarios

The Maintenance Worker and Boundary Individual scenarios apply to the time period when institutional control is active and are analogous to the scenarios of the same names described in WCS (2007).

The Maintenance Worker is assumed to be present within the administrative boundaries of the closed waste disposal facilities and to be exposed on the surface of the caps. The Maintenance Worker may be exposed via pathways related to

- inhalation of gas-phase radionuclides emanating from the closed facilities,
- inhalation of particulates resuspended from surface soil above the facilities and transported in the atmosphere,

- inadvertent ingestion of surface soil, and
- external dose from surface and near-surface soil.

The Boundary Individual is assumed to be present at a location just outside a 100-m wide buffer zone around the closed facilities. In this regard, the Boundary Individual is analogous to the post-IC Adjacent Resident scenario, although the resident is assumed to be present at this location for a greater fraction of time. The Boundary Individual may be exposed via pathways related to

- inhalation of gas-phase radionuclides emanating from the closed facilities, and
- inhalation of particulates resuspended from surface soil above the facilities.

4.0 Model Implementation

The framework for implementation of the dose assessment in the WCS Site Model is shown schematically in figures described in Section 4.1. An important aspect of model implementation is that potential human exposure is mediated only by natural transport processes (e.g., diffusion, biotic transport) until an assumed oil development period that exists at a time following the modeled structural failure of the concrete cap. At that time, an oil or gas well is assumed to be able to penetrate the buried wastes – whether this event occurs can be modeled probabilistically or forced by the user, as discussed in Section 4.1.2. Both the Oil Field Worker and subsequent receptors after this model time may then be exposed to radioactivity in drill cuttings. In the event that drill cuttings are assumed to be left on the ground surface (air rotary drilling) the radionuclides are incorporated into the GoldSim contaminant transport model surface soil cell (TopSoil) and are susceptible to naturally-occurring environmental transport processes. The handling of borehole cuttings activity is discussed in more detail in Section 4.2.

4.1 Event Probabilities

Four binary dose assessment model states (or events, from the perspective of a dynamic model simulation) may be evaluated in the WCS Site Model. These model states are essentially representations of model uncertainty—they represent uncertainty in the appropriate boundary conditions for the exposure model. This is in contrast to parameter uncertainty, which represents uncertainty in the value of a parameter within a defined model. These model states include

1. whether an oil or gas well is drilled through a disposal facility in the future,
2. if a well is drilled, whether mud rotary or air rotary method is used,
3. whether the On-Site Resident has a home above a disposal facility, and
4. if a home exists, and if a well was previously drilled through the waste, whether the home is located in the area where drill cuttings were disposed (the compounded low probabilities of these events makes the likelihood of this scenario vanishingly small).

As is evident from the wording of the events, some events are dependent on the status of precursor events. As described in subsections 4.1.1 and 4.1.2, possible combinations of these events can be defined by a model user using ‘Switches’ on the GoldSim model control panel to force an event to occur during a simulation. Alternatively, one or more events may be allowed to occur probabilistically in each model realization. The relationship of these Switches to the

overall dose assessment framework is shown schematically for inhalation pathway doses (Figure 2) and ingestion and external pathway doses (Figure 3) below.

4.1.1 On-Site Resident

The presence of a future residence being built upon on a waste facility depends on the likelihood of a resident moving to the general area, and the chance of building directly over one of the waste facilities. If a new residence is built on a facility and if an oil/gas well was previously drilled through the waste, there is a secondary probability that the residence will be constructed in that area of the facility where drill cuttings were left behind.

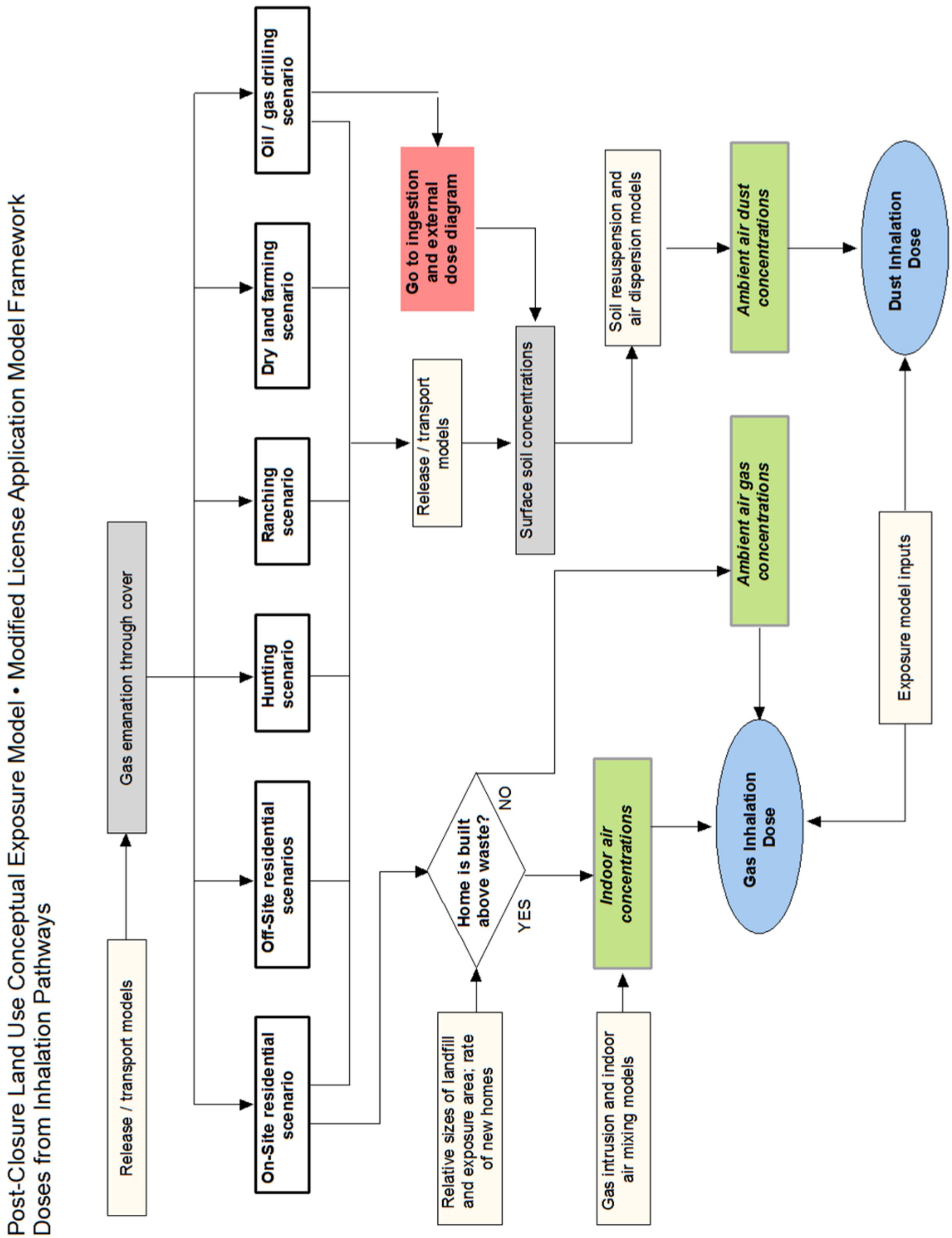

Figure 2. Inhalation Exposure Pathway; Influence of Model State Switches

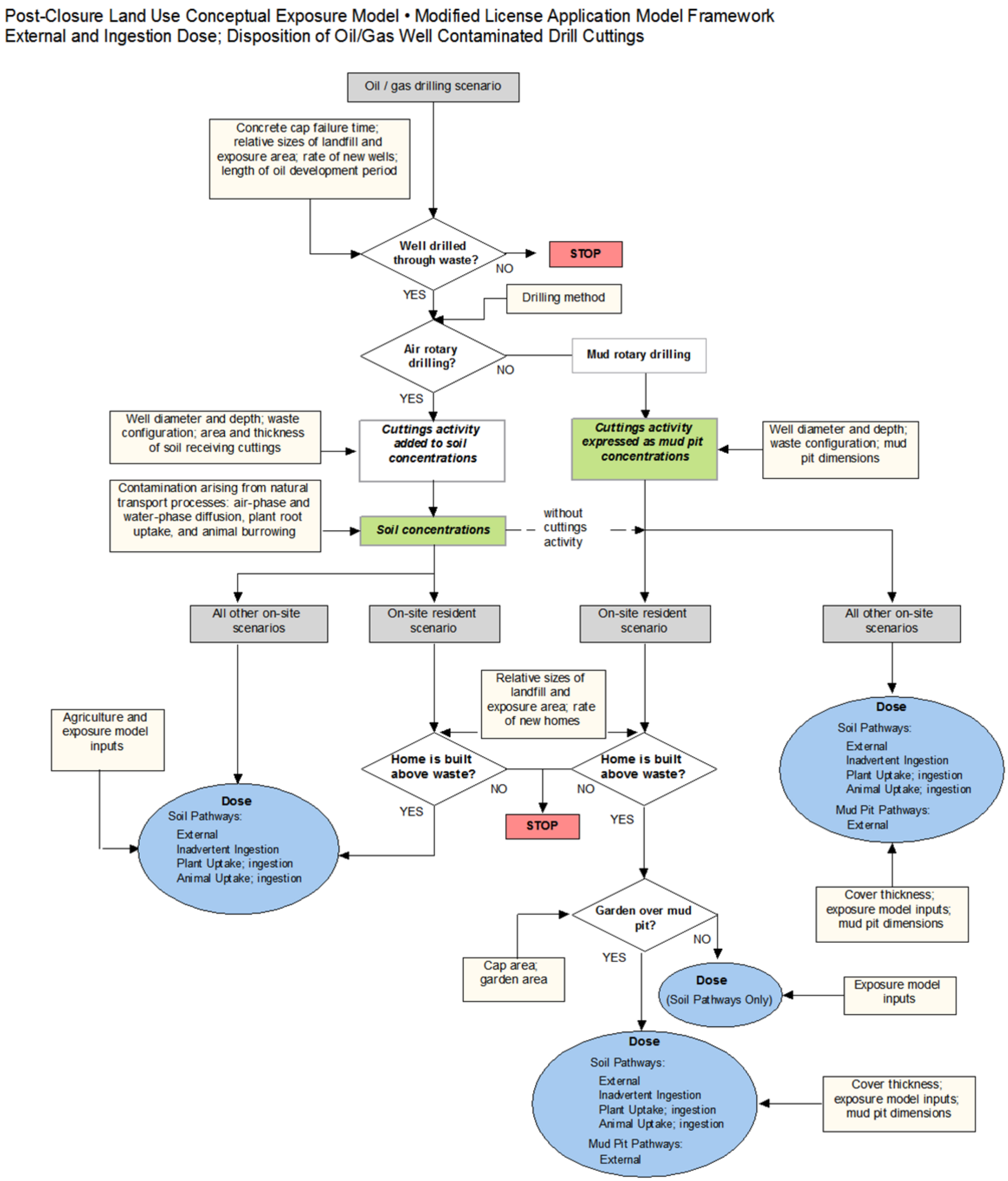

Figure 3. Ingestion and External Exposure Pathways; Influence of Model State Switches

The rate of new home construction is taken from the history of the area currently owned by WCS. Since the first modern settlement occurred about 100 years ago, two homes are known to have been built: the original homestead west of the disposal facilities (south of Baker Spring) and the former ranch house north of Windmill Hill. The area in which homes may be sited at the nominal rate of two per 100 years is assumed to be at least as large as a strip about 1 mile wide along the 4.5-mile stretch of Highway 176 that runs through the WCS facility because both historical homes on WCS property were within 1 mile of the road, and the disposal facilities are also about 1 mile from Route 176. The per-year probability that a home is constructed above one of the waste facilities is calculated as:

new home rate (1/yr) × (disposal unit area (ha) / home siting area (ha))

Whether a home is built at any time after the loss of institutional control is defined using a Poisson distribution with a rate equal to the per-year probability defined above. Using a Switch on the WCS Site Model's Control Panel, the model user may condition the dose assessment on the assumption that a residence exists on a disposal facility, or s/he may allow the event to occur probabilistically.

Once a home exists on a disposal facility, the probability that the home garden is situated above a covered mud pit (assuming that mud rotary drilling was selected, as described in Section 4.2) is calculated as the ratio of the garden area to the disposal unit area. Whether a garden is built above the mud pit is defined using a Poisson distribution with a rate equal to this probability. Similarly, if air rotary drilling was selected by the user, the probability that the home is situated above the dispersal area for the surface-disposed cuttings is calculated as the ratio of the dispersion area to the disposal unit area. Once again, the model user may condition the dose assessment on the assumption that residential exposure to the cuttings occurs when a residence exists on a disposal facility, or s/he may allow the event to occur probabilistically.

4.1.2 Oil and Gas Development

The probability that an oil or gas well is drilled through the CWF or FWF at some time in the future depends on the likelihood of a well being drilled in this general area, and also on the chance that a well is situated over one of the waste facilities.

During or after drilling, it is also possible that radiation associated with the disposed wastes may be identified in the borehole or drill cuttings through the routine use of dosimeters or other detectors related to application of radiation sources for well logging, multiphase flow metering, or other purposes. The events leading to a situation where an oil or gas well is drilled through the waste and cuttings dose may be received is shown schematically in Figure 4. The boxes highlighted in dark outline and bold font indicate the assumptions used in the WCS Site Model dose assessment.

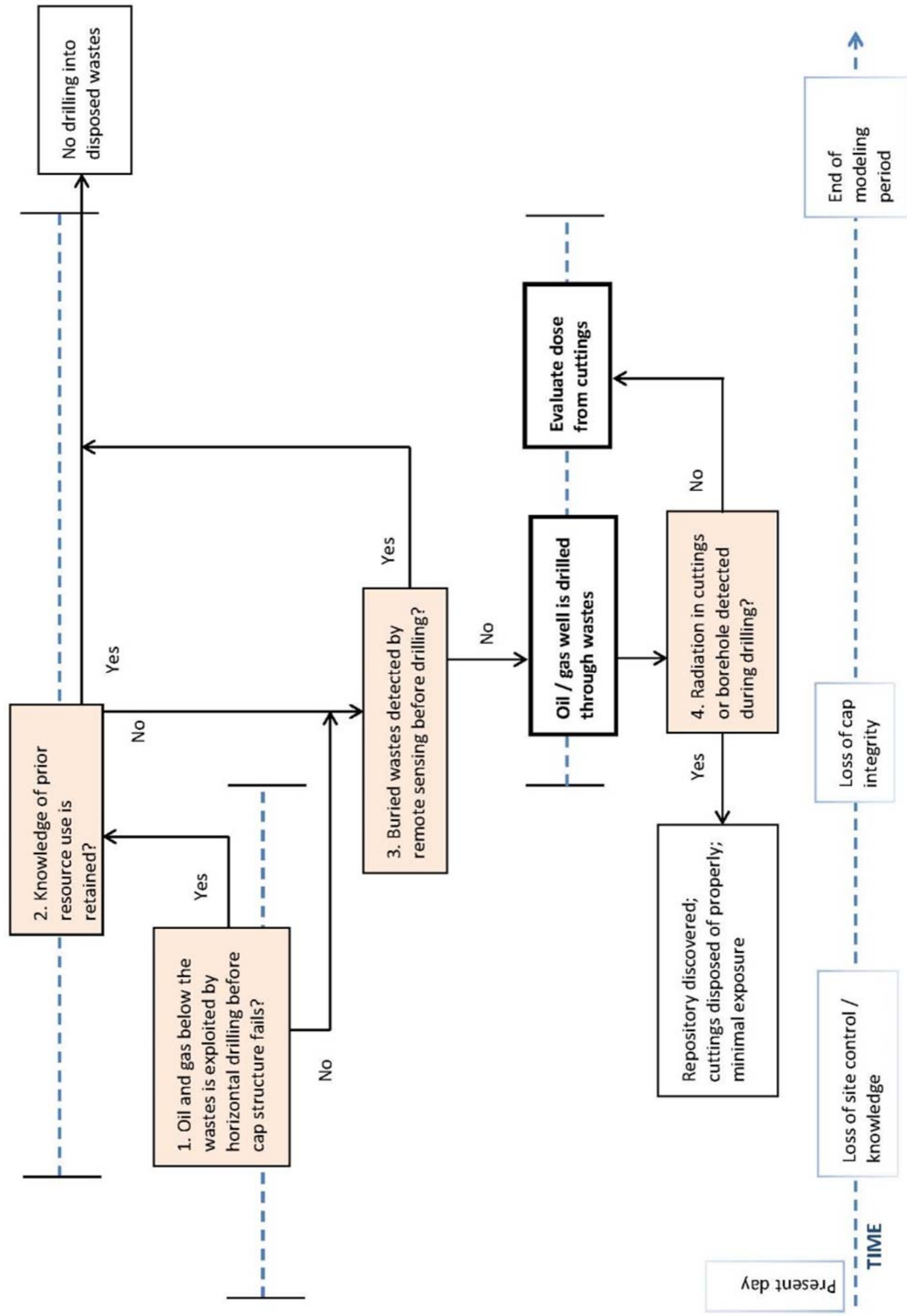

Figure 4. Event Diagram for Occurrence of Cuttings-Related Dose

In the implementation of the dose assessment in the WCS Site Model, it is assumed that if an oil or gas well is drilled through a disposal unit that Oil Field Workers or later receptors may receive radiological dose from contaminated drill cuttings. This effectively assigns a probability of zero to each of the four events shown in Figure 4. The rate of oil or gas well construction is taken from the findings of a 2005 oil well survey described in Volume 16 of the License Application (WCS, 2007). This survey found 5 wells within a circular area of 2.5-km radius from the disposal facilities (an area of 1960 ha). These wells are assigned to an uncertain oil well development period, which is assumed to occur immediately after structural failure of the concrete cap permits a borehole to penetrate the waste.

The per-year probability that a well is drilled through one of the waste facilities is calculated as:

(5 wells / well development period) × (disposal unit area / well survey area)

Whether a hypothetical oil or gas well is drilled within the well development period is defined using a Poisson distribution with a rate equal to the per-year probability defined above. If a well occurs, then oil field work dose is calculated and the radioactivity in drill cuttings becomes available to future receptors in other scenarios. Using a switch on the WCS Site Model's Control Panel, the model user may condition the dose assessment on the assumption that an oil or gas well is drilled through each disposal facility, or s/he may allow the event to occur probabilistically.

4.2 Borehole Cuttings Activity

As noted in Section 4.1.2, it is assumed that if an oil or gas well is drilled through a disposal unit receptors may receive radiological dose from contaminated drill cuttings. The nature and magnitude of such dose is evaluated within the model under a set of assumptions. Briefly, if a well is drilled through a waste disposal facility, then the activity in borehole drill cuttings is assigned either to a layer of contamination in a mud pit (in the case that mud rotary drilling is evaluated) or to a scenario-specific area of surface soil (in the case that air rotary drilling is evaluated). The type of drill method used is selected by the model user using a switch on the Control Panel, in WCS Site Model v0.205.

With respect to mud rotary drilling, the use of a mud pit or reserve pit to hold drill cuttings, and then closing the mud pit with the cuttings in place, may not occur. A November 2012 article in Energy and Environment quotes the president of the Permian Basin Petroleum Association saying that he expects at some point in the future the use of pit liners or closed-loop drill fluid systems will be required in Texas (http://www.eenews.net/public/energywire/2012/11/15/1). There is also evidence that closed-loop systems may actually be more cost efficient in some situations (see Case History 1 in a best management practices publication of New Mexico's Energy, Minerals and Natural Resources Department, http://www.emnrd.state.nm.us/OCD/documents/2000PollutionPreventionBMPs.pdf) and so may come to be adopted based on economic incentives even in the absence of regulatory action.

In the event that mud rotary drilling with a mud pit is the drill method used, the magnitude of cuttings-related dose may be affected by the drilling protocol and the attributes of the mud pit constructed. As discussed in a recent article in a drilling industry publication, shallow surface

holes may first be drilled with one drill rig followed by a second, larger rig to advance the hole to the depths of the oil-bearing strata (http://deepholedriller.com/2012/04/rd20-oil-gas-drill-rig/mixing-it-up/). The size of the mud pit, and the volume of cuttings deposited above the shallow cuttings containing waste unit radioactivity, will be smaller if a surface hole is drilled through a waste unit than if a mud pit were used for drilling to the oil-bearing strata with a single drill rig. However, even if only one drill rig is used, drillers may construct one or more “reserve pits” to hold cuttings that are distinct from a larger mud pit used to hold the recirculating drill fluid.

The events and assumptions related to the exposure conditions and magnitude of cuttings-related dose are shown schematically in Figure 5. The boxes highlighted in dark outline and bold font indicate the assumptions used in the dose assessment in the WCS Site Model.

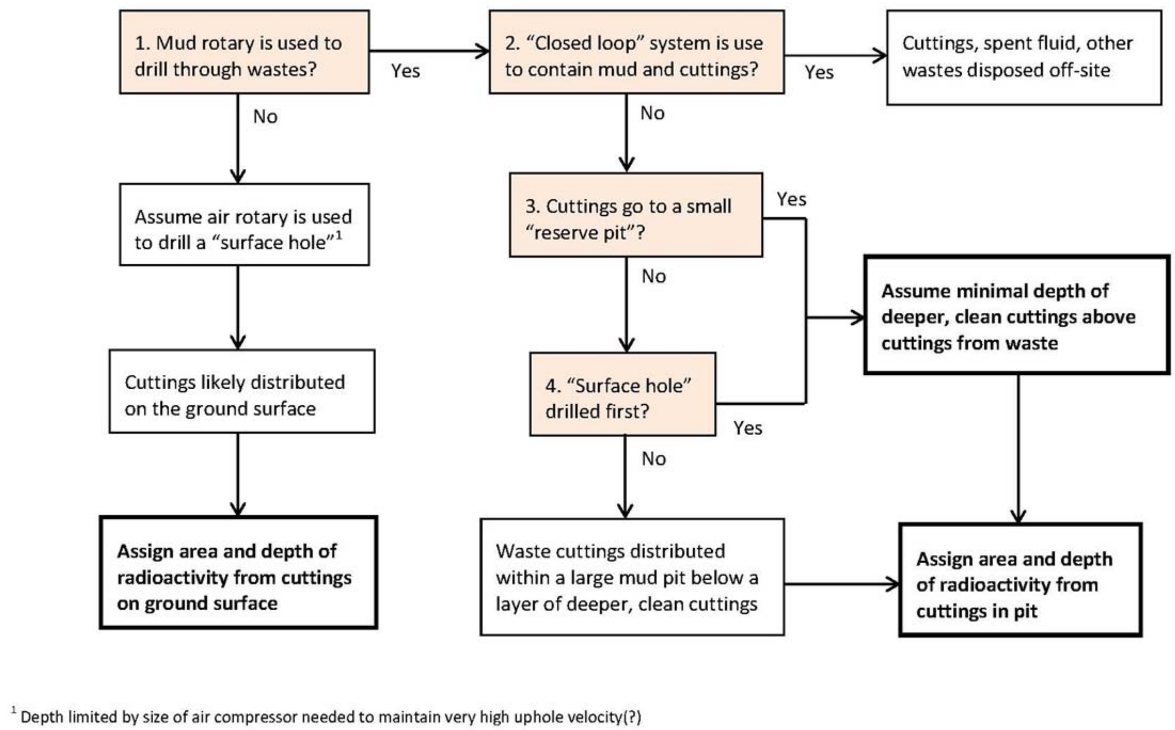

Figure 5. Event Diagram for Nature and Magnitude of Cuttings-Related Dose

The activity in the borehole cuttings is a fraction of the total waste unit area activity of the entire unsaturated zone (UZ) section, from the ground surface to the top of the 225-ft sandstone saturated zone, including the disposal unit. This fraction is calculated as the ratio of borehole area to total model area (the area of the CWF or FWF). It is assumed that no contamination exists below the top of the 225-ft sandstone (the bottom of the UZ). For dose assessment calculations related to the open or covered mud pit (mud rotary drilling), activity concentrations of each radionuclide in the contaminated cuttings (Bq/g or Ci/g) are calculated as:

cuttings activity / (cuttings volume × cuttings density)

External dose associated with exposure to the contaminated cuttings in an open or covered mud pit is calculated using scenario-specific external DCFs that account for the exposure geometry (size of contaminated area, depth of cover material, relative location of receptor) associated with the scenario. Modification of infinite-source soil DCFs for external exposure is discussed in Section 4.4. Because exposure to radionuclides in the covered mud pit may occur at model times much later than the oil well development period, it is necessary to allow for radionuclide ingrowth and decay over time. This is accomplished by assigning the mud pit cuttings activity to a GoldSim “Cell Pathway” element, a specialized element that natively supports these decay and ingrowth calculations.

In WCS Site Model v0.205, dose assessment calculations related to cuttings mixed into surface soil (air rotary drilling), the radioactivity in drill cuttings is directed to the TopSoil model Cell in the contaminant transport component of the WCS Site Model. Once cuttings radioactivity is added to the TopSoil Cell, this activity is susceptible to naturally-occurring environmental transport processes such as diffusion, infiltration, biotic transport, and air dispersion. This is the only point in the current model where events and calculations performed in the Dose Assessment container affect the evolution of the contaminant transport calculations.

The TopSoil Cells for the CWF and FWF encompass the entire surface area of these disposal units. However, the actual area over which air rotary cuttings would be dispersed following drilling is uncertain. The bulk of cuttings may in fact remain within a smaller area, in which case surface soil concentrations would be higher than concentrations that will exist in the GoldSim TopSoil Cells for the CWF and FWF. In order to evaluate the dosimetric impact of the assumed area of soil mixing, the radionuclide soil concentrations in the TopSoil Cells are algebraically modified to estimate concentrations in a smaller area, as described in Section 4.3.2. As was done with mud pit cuttings activity, GoldSim Cell Pathway elements are used to evaluate radionuclide ingrowth and decay for the air rotary cuttings.

4.3 Calculation of Exposure Media Concentrations

Exposure media concentrations used in the dose equations (Section 4.5) are defined here.

4.3.1 Indoor and Outdoor Air

Atmospheric dispersion modeling was performed as part of the October 2011 model (WCS, 2011) for a receptor 100-m distant from the disposal facilities’ northern boundary, and for an offsite (Eunice) location 6 km west of the facilities boundary. Radionuclide concentrations in air above the disposal facility are assumed to be equivalent to those near the boundary (pending new dispersion modeling under PA maintenance). Air dispersion model outputs are given as Chi/Q values, the ratio of breathing-zone air concentration (Chi) to the gas or particulate emission rate (Q) used in the air modeling simulations.

Indoor air concentrations of gas-phase radionuclides are calculated using an Alpha_Residence term, which is the soil gas attenuation factor (alpha). Alpha is simply the ratio of indoor air concentration to the concentration in soil gas below a building (EPA, 2012). The equivalence of

alpha measurements for radon and volatile organic compounds (VOCs), the analytes from which the alpha values used in this report were measured (EPA, 2012), is based on the practice of using radon as a tracer for measuring VOC alpha values when VOC source strength is low (McHugh et al., 2008; DoD, 2008).

For example, gaseous air radionuclide concentrations on the disposal unit cover are

$$\text{AirConcGas\_Cover (pCi/m}^3\text{)} = \text{GroundFluxGas\_Cover} \times \text{DisposalUnit\_Area} \times \text{Chi\_Q\_Boundary},$$

where

GroundFluxGas_Cover =	flux of gas-phase radionuclides emanating from the cap into the atmosphere (pCi/m^2-s),
DisposalUnit_Area =	surface area of the disposal unit (m^2), and
Chi_Q_Boundary =	the ratio of gas flux to breathing zone concentration at the (downwind) border of the disposal facility (g/m^3 per g/s).

Similar calculations are performed for gas and particulate air concentrations for each receptor at a different location.

4.3.2 Soil

As discussed in Section 4.2, if air rotary drilling of an oil or gas well occurs, the radioactivity in drill cuttings is assigned to the model's TopSoil surface soil Cell of the disposal facility. In order to evaluate the dosimetric impact of the assuming a smaller soil area in which cuttings are mixed, the radionuclide soil concentrations in the TopSoil Cells are algebraically modified to estimate concentrations in a smaller area. Radionuclide ingrowth and decay for radioactivity in air rotary drill cuttings is evaluated using separate GoldSim Cell Pathway elements. Because no environmental transport occurs in these Cells, the relative cuttings activities in the TopSoil cells and Cuttings Cells will begin to diverge with time after the drilling period.

The general approach for assessing the effect of a varying soil mixing area for air rotary drill cuttings is to subtract the contribution of cuttings activity from the total surface soil activity, and then adding to this value the decayed cuttings activity multiplied by the ratio of the (smaller) area to the area of the entire cap:

$$(\text{ TopSoil concentration} - \text{Cuttings Cell concentration }) + [\text{ Cuttings Cell concentration} \times (\text{ cap area / assumed mixing area })]$$

The first term in this equation is restricted to a minimum value of zero. In the second term, the assumed mixing area is restricted to a size smaller than the area of the cap (the area of the model's TopSoil cell). This adjustment is performed for the On-Site Resident and Oil Field Worker scenarios, where the exposure areas may be smaller than the entire area of a disposal facility. In the case of the Ranching, Hunting, and Farming scenarios exposure areas are always larger than the size of a disposal facility, and therefore no adjustment of this sort is required.

4.3.3 Produce and Grain

Radionuclide concentrations in produce (wet weight) are calculated from garden soil concentrations using plant (dry weight) / soil concentration ratios and a dry-to-wet plant conversion factor. Plant-soil ratios are dimensionless concentration ratios defined for each radioelement in the GoldSim model. A similar calculation is performed for grains using farming area radionuclide soil concentrations. For example,

ProduceConc (pCi/g wet weight)
= GardenSoilConc × CR_Produce × DryWetConversion_Produce,

where

GardenSoilConc =	radionuclide concentrations in garden soil (pCi/g),
CR_Produce =	plant-to-soil concentration ratio for produce (fruits) (pCi/g dry plant per pCi/g soil), and
DryWetConversion_Produce =	conversion factor for dry weight to wet weight in produce.

Similar calculations are performed for grain.

4.3.4 Beef and Game Meat

Radionuclide concentrations in beef and game meat are calculated from the relevant soil radionuclide concentrations using transfer factors (TFs) which specify the amount of a chemical element taken up into muscle tissue as a function of the daily intake rate of that element by the animal. The same TFs are used for both beef and game meat with the exception of hydrogen (H-3) and carbon (C-14), for which differences pertain to inputs used in the C-14 and H-3 animal uptake models described in Section 4.3.5.

Radionuclide uptake by beef cattle and game is assessed based on ingestion of forage and direct soil ingestion during grazing. For simplicity, and because the exposure areas for ranching and hunting have been defined as identical, a single calculation of forage plant concentrations is performed for application to both beef cattle and mule deer:

ForageConc (pCi/g wet weight)
= SoilConc_Ranching × CR_Forage × DryWetConversion_Forage,

where

SoilConc_Ranching =	radionuclide concentrations in ranching soil (pCi/g),
CR_Forage =	plant-to-soil concentration ratio for forage plants (pCi/g dry plant per pCi/g soil), and
DryWetConversion_Forage =	conversion factor for dry weight to wet weight in forage.

The concentrations in beef are built on the forage concentrations thus:

RanchBeefConc
= RanchedBeef_TF × [(ForageIngestionRate_Cattle × ForageConc)
+ (SoilIngestionRate_Cattle × SoilConc_Ranching)]

where

RanchedBeefTF = soil-to-beef transfer factor (pCi/g per pCi/d),
ForageIngestionRate_Cattle = forage ingestion rate for beef cattle (g wet weight/day),
ForageConc = radionuclide concentrations in forage (pCi/g wet weight),
SoilIngestionRate_Cattle = soil ingestion rate for beef cattle (g/d), and
SoilConc_Ranching = radionuclide concentrations in ranching soil (pCi/g).

Concentrations in hunted game are calculated analogously.

4.3.5 Tritium and Carbon-14 Biota Models

Models for estimating concentrations of tritium and carbon-14 in plant and animal tissues are based on Appendices C and D of NUREG/CR-5512 (NRC, 1992). The plant-to-soil concentration ratio for carbon-14 is provided as a value based on experimental data. For tritium, a plant-to-soil concentration ratio is calculated based on an assumed equilibrium between soil and plant moisture as described below.

For animal products, the tritium concentration model is based on the relationship of tritium intake per mass of total hydrogen intake, assuming that this relationship reflects the activity of tritium per mass of hydrogen in the product. Total hydrogen intake is defined based on fresh forage, stored feed, and water. The animal products model for carbon-14 is analogous to that of tritium, minus a contribution of carbon from water. Only the denominator (total mass of hydrogen or carbon intake per day) is defined here, the activity of tritium or carbon-14 consumed by the animal in forage and soil is addressed in the calculation of beef and deer meat concentrations where the transfer factors are applied.

The tritium plant-to-soil concentration ratio is

CF_plant_tritium
= water_to_H × f_Hv × SA_wvH / GravWaterContent_H3,

where

water_to_H = mass conversion from water to hydrogen (g H2O / g H),
f_Hv = mass of hydrogen per mass of plant tissue (g H / g wet weight),
SA_wvH = specific activity equivalence of tritium in plant and irrigation water (pCi tritium / g H plant wet weight per pCi tritium / g H in water), and
GravWaterContent_H3 = gravimetric water content of irrigated garden soil (g soil water / g bulk dry soil).

The tritium transfer factor for beef or game meat is

TF_meat_tritium
= 1 / (ForageIngestionRate × f_H_forage + IR_water × f_H_water × WatDens),

where

ForageIngestionRate = forage ingestion rate for animal (g wet weight/d),

f_ H_forage =	fraction of fresh forage that is hydrogen (equivalent to f_Hv),
IR_water =	water ingestion rate of animal (L/d),
f_H_water =	fraction of hydrogen comprising water (calculated as 1 / water_to_H), and
WatDens =	density of water (1000 g/L)

The carbon-14 transfer factor for beef or game meat is

TF_meat_carbon
= 1 / (ForageIngestionRate × f_C_forage)

where,

f_ C_forage = fraction of fresh forage that is carbon (equivalent to f_Hv).

4.4 Derivation and Application of Dose Conversion Factors

Dose conversion factors (DCFs) are derived using models and data that represent the physics and biology of the interaction of the human body with radiation. Specifically, the DCFs are used to assess a total effective dose equivalent (TEDE), where radiation and tissue weighting factors are used to account for the radiosensitivity of various target organs and the biological effectiveness of different types of ionizing radiation. Internal DCFs (typically in units of Sv/Bq, for ingestion and inhalation) are used to convert from an exposure or intake to an internal dose delivered to various organs and tissues. Separate inhalation dose coefficients are published for different lung absorption rate classes. For external exposure, different dose coefficients exist depending upon whether the receptor is immersed in a plume of radioactive contaminants (such as air), is standing on a surficially contaminated material, or is standing on the surface of a ground volume source. Only those dose coefficients related to external exposure to a ground volume source are employed in the WCS Site Model dose assessment.

The principal reference for internal DCF values is ICRP Publication 72 (ICRP, 1996). A secondary reference is the older Federal Guidance Report 11 (EPA, 1988) which is provided primarily for continuity with earlier license application dose calculations. A Control Panel switch is provided to the user in order to allow selection between Federal Guidance Report 11 or ICRP Publication 72 internal DCF values. External soil volume source DCFs are referenced to Federal Guidance Report 13 (EPA, 1999). The specific sources within these references are described in Table 1.

The references cited in the previous paragraph provide DCF values for individual radionuclides including those with relatively short half-lives below the cut-off half-life of 300 days used to define GoldSim Species for the WCS Site Model (see the *Inventory* white paper). For these Species, DCFs used in the model must account for the contribution from short-lived radioactive progeny. The summation of the contribution of short-lived progeny to calculate the "+D" (plus daughters) DCFs used in the model is shown in the worksheet '*DCF roll ups*' in the Excel workbook *WCS Site Model Parameters.xlsx*. The decay chains and branching fractions related to

short-lived progeny that were applied in calculating "+D" DCFs were taken from *Nuclear Wallet Cards* (Tuli, 2005) and are shown schematically in the *WCS Site Model Parameters.docx*.

4.4.1 Standardizing Units for Gas-Phase DCFs

ICRP Publication 72 (1996) provides separate DCFs for gas-phase radionuclides, including the Species argon-39 and krypton-85, with units (Sv/Bq–hr–m^{-3}, or Sv/hr per Bq/m^3) that incorporate an inhalation rate. The radon-222 inhalation DCF derived from radon working level values (Calculation Sheet WCS015) is also expressed in these units. To convert these gas-phase DCFs to the common internal DCF units of Sv/Bq, the DCFs were divided by an inhalation rate according to:

$$\text{gas-phase DCF (Sv/Bq–hr–m}^{-3}\text{) / InhRate\_Rn (m}^3\text{/hr)},$$

where

InhRate_Rn = inhalation rate for a "standard worker" associated with a radon working level month.

A radon working level is defined as any combination of short-lived progeny of Rn-222 in one liter of air that results in the emission of 1.3×10^5 MeV of potential alpha decay energy (ICRP, 2003) and a working level month (WLM) is defined as exposure at 1 WL for a 170-hr working month.

4.4.2 Derivation of an Inhalation DCF for Radon-222

The derivation of an inhalation DCF for radon-222, and associated progeny equilibrium factors (F) for indoor and outdoor environments, is described in Calculation Sheet WCS015. In summary, an inhalation DCF for radon-222 was calculated from a value of 5 mSv/WLM using definitions and values from ICRP (2010). A value of F for indoor air was taken from ICRP (2010), and an equilibrium factor for outdoor air was calculated from the indoor air F according to the relative air exchange rate in outdoor and indoor environments.

The inhalation DCF for radon-222 is calculated assuming equilibrium with the short-lived progeny (polonium-218 and polonium-214) that are responsible for the great majority of the inhalation dose. This DCF is then applied to indoor and outdoor environments by multiplying the DCF by the value of F specific to either indoors or outdoors.

4.4.3 Derivation of External DCF Modifying Factors

The external DCF values referenced from EPA (1999) pertain to a soil volume source of effectively infinite area and depth. These DCFs must be modified to apply to external dose geometries where the source is of less-than-infinite dimensions, or where the source is overlaid by an uncontaminated cover material. The DCF modifying factors are applied as multipliers to the external DCFs in the dose equations, resulting in scenario-specific external DCFs. The assumptions employed for the derivation of DCF modifying factors, and the details of their calculation using the RESRAD computer code, are described in Calculation Sheet WCS014.

Modifying factors are applied to the external DCFs to address the following less-than-infinite external exposure geometries:

1. a 1-cm-thick (TopSoil) layer across the entire (effectively infinite area) cap,
2. a 15-cm-thick (UZ1) soil layer beneath the TopSoil layer across the entire (effectively infinite area) cap,
3. a 15-cm-thick soil layer for a garden-sized source area,
4. oil well drill cuttings in a backfilled (covered) mud pit that post-drilling receptors may walk over, and
5. oil well drill cuttings in an open mud pit (with overlying drill fluid and clean cuttings) where an oil field worker may be exposed at the edge of the pit.

For exposure geometries 4 and 5, DCF modifying factors are calculated in order to assess a range of potential cover thicknesses, to support an evaluation of the impact of uncertainty in cover thickness on the dose assessment results.

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