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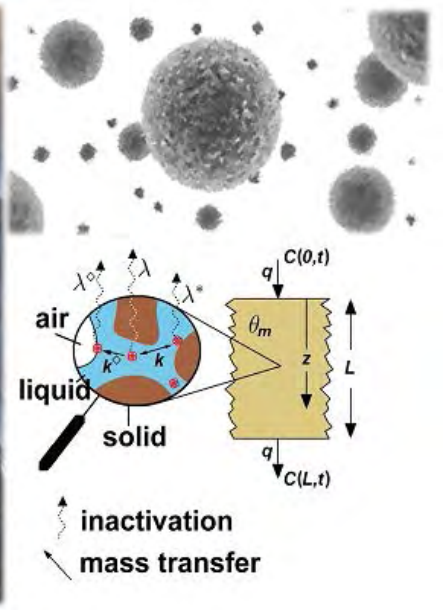
Exposure Assessment of Livestock Carcass Management Options During a Foreign Animal Disease Outbreak



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Exposure Assessment of Livestock Carcass Management Options During a Foreign Animal Disease Outbreak

by

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Acronyms and Abbreviations

Acronym/Abbreviation	Stands For (Country or Agency Affiliation)
AERMOD	AMS/USEPA Regulatory Model Improvement Committee Model (air dispersion model)
AMS	American Meteorological Society
APHIS	Animal and Plant Health Inspection Service (USDA)
°C	degrees Celsius
cm	centimeter(s)
DAF	Dilution Attenuation Factors
DHS	Department of Homeland Security (U.S.)
DW	dry weight
EPACMTP	USEPA Composite Model for Leachate Migration with Transformation Products
°F	degrees Fahrenheit
FAD	foreign animal disease
ft	foot (feet)
FAD	Foreign Animal Disease
FMD	foot and mouth disease
FMDv	foot and mouth disease virus
g	gram(s)
h	hour(s)
HHRAP	Human Health Risk Assessment Protocol (USEPA)
ID_{50}	infectious dose causing illness in 50 percent of the exposed population
Kd	soil/liquid partition coefficient
kg	kilogram(s)
km	kilometer(s)
L	liter(s)
m	meter(s)
m^3	cubic meter(s)
mL	milliliter(s)
NHSRC	National Homeland Security Research Center (USEPA)
PFU	plaque-forming units
PPE	personal protective equipment
SOP	standard operating procedure
$TCID_{50}$	50 percent tissue-culture infectious-dose
µm	micrometer(s)
UM CAHFS	University of Minnesota's Center for Animal Health and Food Safety
U.S.	United States (adjective)
USDA	United States Department of Agriculture

Acronym/Abbreviation	Stands For (Country or Agency Affiliation)
USEPA	United States Environmental Protection Agency
UV	ultra violet

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Executive Summary

As a product of the collaborative research between the U.S. Environmental Protection Agency's (USEPA's) Office of Research and Development and the U.S. Department of Agriculture's Animal and Plant Health Inspection Service (APHIS), this report evaluates livestock carcass management options following a foreign animal disease outbreak. This assessment helps to inform a scientifically-based selection of environmentally protective methods in the event of an outbreak.

The foreign animal disease selected for this assessment is foot and mouth disease. The foot-and-mouth disease virus (FMDv) infects and is transmitted by livestock including cattle, swine, and goats. FMDv does not typically infect humans and is not considered a threat to public health. Healthy livestock can become infected by inhaling or ingesting infective FMDv released from live animals or the carcasses of infected animals. The potential for carcasses to release infective FMDv is greatest in the hours and days following death as the carcasses begin to decompose and fluids are released. Potential exposures become less likely with time because FMDv does not replicate outside a living host and is progressively inactivated by biological decay.

If carcasses cannot be managed immediately after death, the temporary carcass storage pile appears to be the most likely source to possibly expose nearby livestock. This assessment estimates livestock exposure to FMDv released from a temporary storage pile where carcasses are placed for 48 hours while further management is prepared. The assessment also considers seven well-established carcass management options with sufficient capacity for a large-scale mortality: on-site open burning (pyre), on-site air-curtain burning, on-site unlined burial, on-site composting, off-site fixed-facility incineration, off-site landfilling, and off-site carcass rendering.

Qualitative rankings of the three off-site options are presented in Table ES-1. Commercial incinerators would totally inactivate FMDv, and rendering facilities similarly apply sufficient heat for enough time to inactivate the virus. Viable (i.e., potentially infectious) FMDv in carcasses placed in landfills could contribute to leachate, however, livestock are not likely to come in contact with the leachate collected and managed under regulatory requirements. For all the off-site options, all releases to the environment (e.g., incinerator emissions to air, rendering facility discharge to surface water) are restricted by, and are assumed to comply with, normally applicable federal regulations. For these reasons the off-site options are not included in the quantitative assessment. However, this assessment does not consider facilities operating under emergency exemptions to environmental law, because, in those cases, normal federal restrictions on emissions and effluent would not be in force. In such cases, additional assessment of off-site options would be warranted.

Table ES- 1. Ranking of Off-Site Livestock Carcass Management Options for Microbes

Rank[a]	Management Option	Principal Rationale
H	Off-site Incinerator	Thermal destruction of all microbes occurs. Ash is landfilled.
M	Off-site Rendering	Thermal inactivation of all microbes except prions occurs. Workers are protected from prion exposure with the use of PPE.
L	Off-site Landfill	Containment, includes liner, leachate collection, and cover material, but no thermal destruction. Cattle are not likely to come in contact with landfill leachate collected and managed under normally applicable regulations.

Abbreviations: H = Highest rank; L = Lowest rank; M = Middle rank; PPE = personal protective equipment

[a] Relative and absolute risks from microbial pathogens depends on initial concentrations in healthy cattle, which is unknown.

FMDv releases from the four on-site carcass management options (Table ES2) are less controlled than releases from the off-site options. Both open burning and air-curtain burning thermally inactivate FMDv particles. Composting also involves partial or complete thermally inactivation. In addition, large animal composting typically takes enough time for complete biological inactivation. The containment provided by on-site burial prevents the release of FMDv particles to air, but leaching from the burial trench has the potential to reach ground water similar to the temporary storage pile.

Table ES- 2. Ranking of On-site Livestock Carcass Management Options for a Foot and Mouth Disease Outbreak

Rank	Management Type	Principal Rationale
1	Open Burning and Air-curtain Burning	Thermal descruction of all FMDv.
2	Composting	Bulking material contains almost all FMDv from releases to air and soil. Thermal inactivation and biological decay eliminate FMDv before composting is complete.
3	Burial	Cover soil contains releases to air. If a number of conditions are met, leaching has the potential to infect cattle that drink water pumped from a ground water well.
4	Temporary Storage	Cattle can be infected by inhaling or ingesting FMDv emitted to air from a nearby storage pile. If a number of conditions are met, leaching has the potential to infect cattle that drink water pumped from a ground water well.

FMDv, foot and mouth disease virus

Exposures of healthy livestock to releases from an unlined temporary storage pile of 100 carcasses are assessed. Exposure pathways include inhalation of airborne FMDv particles, ingestion of virus particles that settle on foraged vegetation, and ingestion of well water containing virus particles leached through soil to ground water. The potential for exposure is affected by several site-specific factors such as the scale of mortality, distance from the source,

and soil type and depth. An uncertainties assessment evaluates how exposure estimates vary when these parameter values are changed over several orders of magnitude.

Assuming no preferential pathways in the underlying soil, the assessment finds that with at least 1 meter (m) of soil above the water table, there is a high probability of 99.99% attenuation of FMDv before reaching ground water. Dilution attenuation and biological decay provide further reduction of infective FMDv depending on the size of the storage pile, distance to the well, and rate of ground water flow. Inhalation is the more likely cause of exposure because airborne virus particles can travel more quickly through air than through the ground water pathway. In addition, there are fewer barriers to a complete exposure pathway for the air pathway than for the ground water pathway, which includes such considerations as well depth and placement.

This report provides information to compare options and support decision-making in the event of an actual foreign animal disease outbreak. Managers can use this report with site-specific information to identify possible exposure pathways, to determine whether complete exposure pathways actually exist, and to evaluate which carcass management options are compatible at their site and which are least likely to expose healthy livestock to FMDv.

1. Introduction

Established by the Department of Homeland Security (DHS), the National Response Framework is a single comprehensive approach to domestic incident management.[1] The framework provides a context for DHS and other federal departments and agencies to work with each other and communities to prevent, prepare for, respond to, and recover from hazards such as natural disasters, acts of terrorism, and pandemics.

Mass livestock mortalities can result from a natural disaster, a foreign animal disease outbreak, a chemical or radiological incident, or from other large-scale emergencies. Proper management of livestock carcasses following large-scale mortalities protects humans, livestock, and wildlife from chemical and biological hazards; maintains air, water, and soil resources; protects ecological resources and services; and enhances food and agricultural security. In support of the National Response Framework, the United States Environmental Protection Agency (USEPA) Office of Research and Development's Homeland Security Research Program, and the United States Department of Agriculture's (USDA's) Animal and Plant Health Inspection Service (APHIS) are collaborating in research to ensure proper management of animal carcasses following major environmental incidents.

1.1 Purpose and Scope

Exposure Assessment Objective

The objective of this assessment is to support planning for environmentally protective livestock carcass management methods in times of emergency by providing scientifically-based information on potential hazards to human health, livestock, wildlife, and the environment.

This report focuses on relative exposures and hazards for different livestock carcass management options in the event of a Foreign Animal Disease (FAD) outbreak. Selection of foot and mouth disease (FMD) virus (FMDv) as the FAD agent for a hypothetical outbreak is described in Problem Formulation in Section 2. This report is preceded by *Exposure Assessment of Livestock Carcass Management Options During Natural Disasters* (USEPA 2017).

The exposure assessment for FAD virus-infected livestock carcasses builds on earlier research, peer-reviewed data and existing models involving a variety of carcass management options (e.g., pyre construction and fuels), scale of mortality, and site conditions as assumed in the case of mass livestock mortalities from a natural disaster (USEPA 2017). Additional assumptions required for FMDv-infected carcasses are described in this report.

FMDv is easily spread and can be transmitted via multiple pathways and exposure routes (USDA 2013a). However, FMDv primarily infects and is transmitted by livestock; the risk to public health posed by this virus is low (Bauer 1997; Prempeh et al. 2001). Adoption of biosecurity measures mitigate exposure of other susceptible livestock (and humans) to FMDv via many

[1] Information about the National Response Framework is available at https://www.fema.gov/media-library/assets/documents/117791.

pathways (USDA 2014a). Most significantly, USDA recommends immediately identifying Infected Premises[2] and euthanizing in-contact susceptible livestock.

As discussed in Section 2.1, the duration of survival of most FMDv in skeletal muscle of a livestock carcass is short due to changes in pH that accompany *rigor mortis* and inactivate the virus (USDA 2013c). Thus, the highest potential for exposures of other livestock to FMDv will occur before complete *rigor mortis* during pre-management activities such as carcass handling, temporary storage, and transport.

The purpose of this assessment is to provide information about the potential sources of FMDv exposure to uninfected livestock during management of infected carcasses. In addition, the assessment can support future carcass management decisions by highlighting parameters (e.g., soil type, depth to ground water) that influence chances of the spread of FMDv via specific pathways (e.g., leaching to ground water that supplies neighboring livestock with drinking water). The findings also might help to identify the most beneficial mitigation measures for minimizing potential exposures at actual carcass management sites.

1.2 Report Organization

This report is organized in six sections. Section 2 explains the conclusions of problem formulation for the assessment, while Section 3 describes the approaches for estimating FMDv releases from carcasses, FMDv fate and transport, and exposure of other live, susceptible species. Section 3 also discusses transmission of FMDv by insects and other animals. Section 4 presents the results of the exposure assessment and uncertainty analysis, and discusses how the findings may be applied to varying site-specific situations. The report concludes with quality assurance documentation in Section 5 and literature cited in Section 6.

[2] Infected Premises are defined as location(s) where presumptive or confirmed positive case(s) were identified based on laboratory results, compatible clinical signs, FMD case definition, and international standards. The Infected Premises is within the Infected Zones (USDA 2014a).

2. Problem Formulation

Problem formulation for the exposure assessment defines the scope of the assessment and simplifying assumptions used to allow comparison among the different carcass management options. Problem formulation for the FAD outbreak scenario builds on a previous assessment of managing livestock carcasses following a natural disaster (USEPA 2017). This assessment uses many of the same assumptions related to the site setting, environmental conditions, and the design and use of the carcass management options described in that report (USEPA 2017). This assessment starts with a base case similar to the previous case (USEPA 2017), but also considers several soil types and varying distances to the ground water table. In the development of the evaluation process, no primary data are gathered and the project relies on secondary data for the analysis. Given the limited availability of data, the screening process outputs likely exhibit high levels of uncertainty. Following the base case, uncertainty analyses are conducted for parameters that are highly variable in the real world (e.g., number of carcasses) or for which best estimates are highly uncertain (e.g., FMDv release rates from carcasses).

The base case for the assessment assumes 45,360 kilograms (kg) of carcasses for all management options, as in the natural disaster assessment (USEPA 2017). For cattle, that mass would equal 100 animals if they each weighed 454 kg (USEPA 2017). Though the base number might be relevant based on the past incidents of catastrophic losses of livestock and their associated large-scale disposal efforts (NBACC 2004), 100- to 1000-fold increase in base case could require appropriate scale-up and sensitivity analysis during such catastrophic large-scale event. For the FMD outbreak scenario, all animals in a single herd of cattle are assumed to be infected with FMDv, although individual viral loads vary when culling cattle begins. Appropriate authorities and veterinarians confirm the outbreak and identify the animals to be culled. Animals are collected as they are euthanized and placed in a temporary storage pile. Receptors of concern are presumably uninfected cattle in a separate herd pastured near the outbreak location (e.g., a neighboring farm). The neighboring cattle drink water pumped from a ground water well that is down-gradient from the carcass management location. The neighboring cattle also graze on pasture that might be downwind from location(s) where presumptive or confirmed positive case(s) were identified based on laboratory results, compatible clinical signs, FMD case definition, and international standards.

No other microbial hazards or chemical hazards are considered in this FAD virus assessment. Exposures to chemicals or naturally occurring microbes from carcasses managed following a natural disaster were investigated in the previous report (USEPA 2017) and occur independently from exposure to an FAD virus.

To prevent spread of FMD, many actions are required to minimize the chance that viable (i.e., infective) FMDv reaches susceptible animals at a dose sufficient to cause infection, as described in USDA/APHIS's *Foreign Animal Disease Preparedness and Response Plan*/*National Animal Health Emergency Management System Guidelines* (USDA 2014b). As part of the outbreak response, some livestock are culled according to USDA/APHIS's policy on stamping-out and depopulation (USDA 2014a). As part of this policy, USDA/APHIS advises that cattle and other

susceptible livestock that meet the FMD presumptive positive case definition[3] be culled as soon as possible, but no later than 24 hours following the index case (USDA 2014a). The guidance also specifies that all cattle in the Infected Premises be culled.

Beyond the Infected Premises is the Infected Zone[4], which includes susceptible animals that might have been infected via contact with infected animals or contact with people or equipment or other surfaces with viable FMDv. The perimeter of the Infected Zone is at least 3 km (~1.86 miles) from the site of the index case (USDA 2014a), but depends on the travel patterns for the livestock herd that includes the positive case. Beyond that, USDA defines a Buffer Zone[5] of at least 7 km (~4.35 miles) beyond the perimeter of the Infected Zone, and specifies that a Surveillance Zone should be established beyond the Buffer Zone.

Cattle beyond the Infected Premises might or might not be culled, depending on whether vaccination is used to suppress FMDv replication (USDA 2014a). Quarantine and movement controls are maintained within the Control Area (Infected plus Buffer Zones) until at least 28 days have elapsed since the decontamination of all confirmed Infected Premises and negative results are found for all surveillance activities (USDA 2014a). Thus, no other susceptible livestock will be brought in to repopulate the outbreak farm site for at least 28 days after the outbreak site is cleared (FMD free).

Also as part of the outbreak response, workers clean and apply disinfectant to equipment, vehicles, and other potentially contaminated surfaces before movement off-site. In its *Foreign Animal Disease Preparedness and Response Plan SOP* [standard operating procedure] *for Cleaning and Disinfection*, USDA/APHIS recommends selecting a disinfectant and disinfection method(s) based on USEPA-registered labels for antimicrobials (USDA 2017). Thus, all products must be labeled for FMDv disinfection. There are currently six USEPA-registered products for FMDv with various active ingredients (USDA 2016). Application of any USEPA-registered disinfectant should follow label instructions for its use and disposal, with measures in place to prevent contamination of ground water or surface waters during or after decontamination activities.

The use of personal protective equipment (PPE) and other biosecurity measures implemented during an FAD outbreak would minimize human exposures to the microbial agents evaluated in the previous assessment (USEPA 2017). Thus, the focus of this is assessment is evaluating potential neighboring livestock exposure to FMDv.

[3] A presumptive positive case is an FMD-susceptible animal that has both epidemiological information indicative of FMD and positive laboratory test results (USDA 2014a).

[4] The Infected Zone is the area around the initial presumptive or confirmed positive case (USDA 2014a), generally an area over which the animal would travel daily (e.g., its barn or other sheltering area to its foraging area or feeding station).

[5] The Buffer Zone is the area around the Infected Zone that includes susceptible animals that might have been exposed to FMDV, either directly or indirectly through exposure to other animals, animal products, fomites, or people from the Infected Zone (USDA 2014a).

2.1 Foot-and-Mouth Disease Virus

FMDv causes a severe, highly contagious disease in cows, pigs, sheep, goats, deer, and other animals with cloven (also termed divided) hooves. The average incubation period[6] for cattle is 2–14 days, 2 or more days for pigs, and 3–8 days for sheep and goats (Ashford 2015). Infected animals exhibit a fever and blisters on the tongue, lips, mouth, on the mammary glands, and around the hooves. The pain and discomfort caused by these blisters can lead to additional symptoms, including depression, anorexia, excessive salivation, lameness, and reluctance to move, stand, or eat (USDA 2013a). For many infected animals (including cattle and swine), the lesions and blisters produced by the virus might be so painful that euthanasia is required for the animals' welfare (Aftosa 2015). Although FMDv does not typically result in death, restricting movements of a herd of livestock to contain the disease in a specific paddock can cause severe distress from lack of food and injury from crowding; in such cases, euthanasia would be more humane. Animals in contact with a confirmed or suspected case of FMD (e.g., in the same herd) typically are culled to prevent further spread of the disease (USDA 2103d). Animals in separate herds (i.e., no contact with animals in the infected herd) likely would be tested for FMDv to help owners or managers to decide whether additional livestock should be culled to contain the outbreak.

While FMDv is considered zoonotic, and thus transmissible to humans, human infection is rare. Globally, only 40 human cases were diagnosed between 1921 and 1997 (Bauer 1997). The circumstances associated with human infection with FMDv are not well defined; however, all reported cases had close contact with infected animals. No cases of person-to-person transmission of the virus have been documented world-wide (Aftosa 2015). There are seven major viral serotypes: O, A, C, SAT 1, SAT 2, SAT 3 and Asia 1. Serotype O is the most common serotype worldwide (Prempeh et al. 2001). While most viral strains affect all susceptible host species, some strains have a more restricted host range (Aftosa 2015). In humans, the typical incubation period for serotype O of the virus is between 2 and 6 days. Symptoms in humans are generally mild and self-limiting and include blisters on the hands, tongue, feet, and mouth as well as fever and sore throat. Patients usually recover a week after the last blister formation (Prempeh et al. 2001).

Different livestock species vary in their susceptibility to FMDv. Cattle are highly susceptible to FMDv and have been referred to as "detectors" in some outbreaks (Sakamoto 2011).

The next two subsections describe additional complexities related to evaluating infectivity, survival, and decay of FMDv as part of this assessment.

2.1.1 Measurement of Viruses and Infective Dose

Measuring concentrations of viable (potentially infectious) virus particles in various materials requires a method of visualizing virus infections caused by a small amount of material. Methods generally use dilutions of a virus "stock" (e.g., contaminated medium) applied to cultures of susceptible cells. The plaque assay inoculates susceptible cell monolayers on petri plates that are

[6] Incubation period refers to the time from the moment of exposure to an infectious agent until signs and symptoms of the disease appear.

incubated until cells become visible around the initially infected cell(s). The concentration of the virus stock then can be calculated in plaque-forming units (PFUs) per mL.

The other common method is to add a specified volume of diluted virus-containing fluid (or other materials) to host tissues in the laboratory. [7] The 50-percent tissue-culture infectious-dose ($TCID_{50}$) is a statistical derivative of the PFU assay.[8] It is calculated as the dilution at which half of the replicate solutions contained at least one PFU, making it indicative of cell infection and damage. FMDv $TCID_{50}$ values correlate with an infectious dose ID_{50} values (the dose that would produce infection in 50% of animals (ID_{50}); however, data required to estimate an ID_{50} from a $TCID_{50}$ value are uncertain. Some have speculated that the number of PFUs should be approximately 0.5 to 0.7 times the value derived from a $TCID_{50}$ (ATCC 2012).

Infectious dose. Host animals of the same species can range substantially in their susceptibility to infection. USDA/APHIS has reported "infectious doses" of FMDv for cattle, sheep and goats, and pigs in $TCID_{50}$ equivalents (USDA 2013c; Table 1-2). These infectious doses as well as an estimate of the corresponding PFUs, and common modes of exposure are summarized in Table 2.1. Reported infectious doses for cattle were only 20 $TCID_{50}$ units (or 10 to 14 PFUs, bovine thyroid tissue culture) for inhalation compared to 10^5 to 10^6 $TCID_{50}$ units for ingestion (or 50,000 to 700,000 PFUs, bovine thyroid tissue culture) (Kitching 2002; Kitching and Hughes 2002; Kitching and Alexandersen 2002; Alexandersen et al. 2003). Pigs are similarly less susceptible via ingestion than inhalation exposure (Alexandersen et al. 2002). Infectious dose depends on the route of exposure for many viruses and animals (Sakamoto 2011; USDA 2013c).

One question not answered by those doses is what proportion of animals exposed at the dose will become infected? In general, the concept of "infectious dose" as listed in Table 2.1 is vague and in fact is not included in medical or veterinarian texts (Johnson 2003). The reason is that with many factors affecting viability of viruses and each virus particle's chances of reaching the interior of a cell in which it can replicate, infection becomes a probabilistic process just as the chance of developing cancer from exposure to a chemical mutagen is probabilistic. Moreover, individual animals can be more or less susceptible to FMDv, and only a couple viral units might cause infection in sensitive animals and over 20 PFUs might not cause infection in less sensitive animals.

[7] Typical cell culture tests are conducted using a serial dilution series of doses with typically 10 replicate cell culture wells per dose. The lowest dose(s) (i.e., most highly diluted samples) should produce no infection. The highest dose(s) (i.e., undiluted material) should produce 100% infection (i.e., viable virus replication in all test wells at that dose). One or more intermediate doses should indicate viable virus in only some of the dose replicates (e.g., 30%, 60% for two sequential dilutions). From a model of dose-response that best fits the data from 0 to 100% infection, the $TCID_{50}$ value is calculated.

[8] 50% Tissue culture Infective Dose ($TCID_{50}$) is the measure of infectious virus titer. $TCID_{50}$ might be more common where the lethal dose of virus must be determined or if the virus does not form plaques. $TCID_{50}$ method is a statistical derivative of the PFU assay. Instead of counting individual plaques, multiple replicates of each virus dilution are made and the $TCID_{50}$ titer is calculated from the 50% endpoint where half of the replicates contained at least one PFU.

Table 2-1. Foot and Mouth Disease Minimum Infectious Doses and Mode of Transmission

Species	Infectious Dose	Route of Exposure	Reference[b]	Estimated PFU-Equivalent Dose[c]
Cattle	As low as 10 to 20 $TCID_{50}$[a] inhaled per cow	Inhalation	UM-CAHFS (2014); Kitching (2002)	5 to 14
Cattle	0.06 $TCID_{50}/m^3$	Inhalation	Donaldson AI (2001) in UM CAHFS (2014)	0.03 to $0.04/m^3$
Cattle	1E+05 to 1E+06 $TCID_{50}$	Ingestion	Kitching (2002)	5E+04 to 7E+05
Sheep and Goats	As low as 10 to 20 $TCID_{50}$	Direct contact	UM-CAHFS (2014); Kitching and Hughes (2002)	5 to 14
Pigs	>800 $TCID_{50}$	Inhalation	Alexandersen et al. (2002)	> 400
Pigs	Approximately 1 E+05 $TCID_{50}$	Ingestion	Kitching and Alexandersen (2002)	5E+04 to 7E+04

[a] $TCID_{50}$ = The quantity of virus (generally in 1 mL of fluid or 1 gram of tissue) added to tissue-culture wells (using cells of the appropriate animal group) that result in 50% of the culture wells exhibiting active infection. An infectious dose of 20 $TCID_{50}$ per mL via inhalation is approximately equal to 10 to 14 plaque-forming units (PFUs) per mL (ATCC 2012). Each PFU equals one (or more) viable virus particle.
[b] Complete references are found at the end of the report.
[c] Multiplied $TCID_{50}$ Infectious Dose by 0.5 to 0.7 (see text).

2.1.2 Survival and Biological Decay

Survival refers to the ability of an infectious unit of virus to remain infectious in the environment over a defined period of time (Embrey et al. 2004). FMDv particles can survive in the environment for long periods (e.g., weeks) under a wide range of conditions. Table 2.2 provides an overview of the survival of FMDv associated with changes in temperature and pH. FMDv is inactivated by high temperatures (<50 degrees Celsius [°C]; 122 degrees Fahrenheit [°F]) and acidic or alkaline conditions (pH <6.0 or >9.0) (Cottral 1969; OIE 2013; USDA 2014a). Survival is a function of the medium associated with the virus (e.g., specific tissue, excretions), virus strain, humidity, exposure to ultraviolet (UV) light, pH, and temperature. As a result, there is high variability in viral survival across natural environments (Alexandersen et al. 2003).

Table 2-2. General Survival of Foot and Mouth Disease Virus (FMDv)

Action	Resistance to Low and High Temperature or pH	Survival in Biotic and Abiotic Environmental Media	References[a]
Temperature	FMDv in animal tissues are: ▪ preserved by refrigeration (4°C; 40°F) and freezing (0°C; 32°F); ▪ progressively inactivated by temperatures above 50°C (122°F); ▪ inactivated by treatment with high heat (internal temperature of 70°C; 158°F) for at least 30 minutes.	▪ Can remain viable in muscle, liver, bone marrow, lymph nodes, and blood of slaughtered animals when temperatures are low (i.e., refrigeration, freezing); ▪ Exposure to sunlight has little or no direct effect on infectivity; ▪ May survive for days to weeks in organic matter and days to a year in wool and hides under moist and cool temperatures.	Cottral (1969); OIE (2013); USDA (2014a)
pH	FMDv in animal tissues are quickly inactivated by pH <6.0 or >9.0.	▪ Survives in lymph nodes and bone marrow at neutral pH (6.6–7.3); and ▪ Inactivated in muscle at pH <6.0 (i.e., after *rigor mortis*).	Cottral (1969); OIE (2013); USDA (2014a)

Abbreviations and acronyms: °C = degrees Celsius; °F = degrees Fahrenheit; FMDv = foot and mouth disease virus

[a] Complete references are found at the end of the report.

Even under optimum conditions outside the host animal (e.g., > 70% relative humidity and temperature between 0 and 50°C), in air FMDv inactivates over time due to biological decay (with zero replacement by replication). In addition, at temperatures progressively higher than 50°C, thermal inactivation (fraction viable FMDv inactivated) per unit time increases, with 100% inactivation at 70°C for at least 30 minutes (Cottral 1969; OIE 2013; USDA 2014a). Inactivation rates have not been reported for FMDv in cattle carcasses, specifically. Donaldson and Ferris (1978) reported a biological decay rate of 50% per hour for FMDv in bovine fluid medium.

FMDv survival within a carcass is dynamic and tissue-specific. *Rigor mortis*, the hardening of body muscles after death, occurs about 6-24 hours after slaughter in beef cattle (Edelstein 2014). The pace of *rigor mortis* is influenced by ambient temperature (USDA 2013c): *rigor mortis* is slower at lower temperatures. The virus present in muscle tissue is inactivated when *rigor mortis* reduces tissue pH to below 6 (USDA 2013c). There are also compartments (e.g., bone marrow, lymph nodes, offal [e.g., kidney, liver], other organs) in cattle carcasses in which pH does not change due to *rigor mortis* that could continue to provide a reservoir of virus for extended durations, especially under environmental conditions that favor virus survival (e.g., low temperature) (Alexandersen et al. 2003).

In this assessment, all carcasses are assumed to pass through *rigor mortis* in the temporary storage pile, with tissue pH below 6 inactivating all FMDv in muscle tissue and other non-hardy compartments over the 2 days on the pile. However, some viable FMDv could remain in bone marrow and lymph nodes after 48 hours.

Inactivation of FMDv begins when temperatures are above 50°C (122°F). Heating animal carcasses to a minimum core temperature of 70°C (158°F) for at least 30 minutes completely inactivates FMDv (USDA 2014a). For carcass management, temperatures associated with combustion or where heat is either applied (i.e., rendering) or produced indirectly (i.e., on-site composting) are described in Section 2.2.

2.2 Livestock Carcass Management Options and Assumptions

The management options considered for the exposure assessment are those with documented use following FAD outbreaks or that are likely to have sufficient capacity for large-scale carcass management. These include seven well-established methods, which can be categorized into three groups as shown in Table 2.3.

The carcass management options can be categorized as *on-site* or *off-site*. The on-site management options (i.e., open burning, air-curtain combustion, burial, and composting) typically are performed on the livestock owner's property if a suitable location is available.

Table 2-3. Livestock Carcass Management Options Considered for the Exposure Assessment

Management Type	Specific Management Option
Combustion-based Management	▪ On-site Open Burning (Pyre) ▪ On-site Air-Curtain Burning ▪ Off-site Fixed-facility Incineration
Land-based Management	▪ On-site Unlined Burial ▪ On-site Composting ▪ Off-site Lined Landfill
Materials Processing	▪ Off-site Rendering

Additionally, the carcass management options can be categorized by degree of containment, as summarized in Table 2.4. Containment options prevent or reduce releases of FMDv into environmental pathways that may lead to exposure of healthy livestock. Containment options in the assessment include off-site landfilling, on-site burial, and composting. This assessment does not consider facilities for containment that operate under emergency exemption to environmental law, because, in those cases, normal federal restrictions on emissions and effluent would not be in force. In such cases, additional assessment of off-site options would be warranted.

The containment provided by on-site burial prevents the release of FMDv particles to air, but leaching from the burial trench has the potential to reach ground water. Large animal composting typically takes six to eight months (Looper 2001), enough time for complete biological inactivation. FMDv in carcasses placed in landfills could contribute to leachate, however livestock are not likely to come in contact with the leachate collected and managed under normal regulatory requirements.

Composting also can be considered a treatment option because heat generated during composting can completely or partially inactivate many species of bacteria, viruses, and particularly protozoa and helminthes (Glanville et al. 2006; Ligocka and Paluszak 2008; Wilkinson 2007 as cited in

Gwyther et al. 2011). Core temperatures of the compost windrow should reach approximately 65–71°C for several days or even a few weeks or months depending on the size of the windrow and other conditions (NABCC 2004; Kalbasi et al. 2005). FMDv is 100% inactivated at 70°C for at least 30 minutes (Cottral 1969; OIE 2013; USDA 2014a).

Table 2-4. Containment of Chemical and Microbial Releases from Management Options

Combustion		Land-Based		Material Processing	
On-Site	Off-Site	On-Site	Off-Site	On-Site	Off-Site
Air Curtain	Incineration	Composting	Landfill	Not Evaluated	Rendering
Open Burning (Pyre)		Burial			

= Releases restricted by regulation
= Releases partially restricted by physical barriers
= No barrier to releases

Four of the management options included in Table 2.4 are either combustion based (i.e., on-site air curtain burning, on-site open burning, and off-site incineration) or involve processes where heat is applied (i.e., rendering). Exposures are not estimated for these four carcass management options because they reach temperature and time criteria for FMDv inactivation (i.e., 70°C for at least 30 minutes (Cottral 1969; OIE 2013; USDA 2014a):

- On-site open burning: 550°C (1,022°F) (Bartok et al. 2003);
- On-site air curtain burning: 850°C (1,562°F) (Miller 2015);
- Off-site incineration: 600–1,000°C (1,112–1,832°F) (Chen 2003, 2004; NABCC 2004);
- Rendering: 115–145°C (240–290°F) for 40 to 90 minutes (Meeker 2006).

All of the carcass management options are preceded by activities with the potential to release virus particles. Among these are carcass handling, temporary storage before the selected management option, and transportation of the carcasses from the storage location to the management location. Each of these is discussed and evaluated in the assessment of livestock management options for natural disasters (USEPA 2017) and the sections below. In addition, off-site transportation of carcasses to landfills, commercial incinerators, or rendering facilities offers a possibility of off-site transport of viable FMDv particles.

2.2.1 Carcass Handling

Moving carcasses to and from a temporary storage pile, loading and unloading vehicles, and placing the carcasses in a management unit will require some workers to come in contact with the carcasses. The use of PPE by these workers, in addition to the low risk to public health associated with FMD, suggests that risks to workers are minimal if they follow protocols.

Flying insects and vertebrate scavengers, such as birds or rodents, could spread the virus to other susceptible species after contact with FMDv-infected cattle carcasses during various handling activities (including the loading and unloading of carcasses from heavy equipment or vehicles) (USDA 2013b, 2013c). Animals most likely to contact carcasses during the handling process are insects (e.g., flies) that land and feed on animals. For flies to transmit FMDv mechanically, they would have to settle on neighboring live cattle where the virus might fall off the fly and where

the cattle could subsequently lick the area (e.g., nose). In addition, distances traveled by flies are usually less than 2 miles (3.2 km; a few flies might fly farther; Townsend 1997). Scavenging wildlife (e.g., fox, crow, feral swine, and rats) are less likely to make contact with carcasses during daytime handling processes due to their avoidance of active humans. At night, carcasses would be covered with tarps secured to the ground.

During carcass handling, virus particles could be released to air from external surfaces, including secretions around the head and rear of carcasses. Using heavy machinery also might puncture carcasses, releasing fluids faster than with intact carcasses. There are accounts of transport of virus particles up to 300 km (approximately ~186 miles) by the wind that included travel over a water body (Gloster et al. 1981). Sorensen et al. (2000) modeled a simulated FMDv plume using the computer model Rimpuff and assuming optimal climatic and topographical conditions. The authors concluded that a virus plume produced by 1,000 infected pigs on a farm could reach cattle up to 300 km from the infected pigs. Thus, it is plausible that livestock at farms located outside the FMD response area could become infected under favorable conditions (e.g., cool temperature, high relative humidity). That scenario, however, is based on live pigs exhaling virus for 24 hours, and swine are known to shed FMDv at higher rates than cattle, sheep, or goats (USDA 2013c).

Estimating FMD exposures resulting from carcass handling requires assumptions about the nature, frequency, and duration of handling actions and virus particle release rates for these actions. No data have been found to quantify those parameters. However, the releases are expected to be similar in nature to releases from carcasses piled for 2 days before further management. This assessment assumes that both handling and temporary storage can release FMDv and that handling time is included in the 48-hour period prior to transport of carcasses to management locations (e.g., trench, pyre, off-site transport to rendering plant). Physical disturbance of cattle carcasses might release hide-bound virus particles and FMDv from secretions on the exterior of carcasses; movement with large equipment might puncture carcasses allowing rapid releases of materials from lungs or bowels.

2.2.2 Temporary Carcass Storage

Temporary on-site storage of carcasses might be necessary while available management options are identified and evaluated, while on-site management units are constructed, and while awaiting transportation or completion of other logistical requirements (e.g., obtaining burn permits, obtaining air-curtain burning equipment from off-site). Many state regulations require carcasses to be managed within a specified timeframe, usually within 24 to 72 hours (USDA 2015). For the exposure assessment, on-site storage for 48 hours (2 days) is assumed for all management options.

The location and design of the temporary carcass storage location(s) can affect potential exposures. Carcasses could be stored in a pile on the ground in open air, in a refrigerated storage unit, or in containers (USDA 2015). Carcasses on the ground could be covered with a tarp, soil, or other material, or left uncovered (USDA 2005). Carcasses might be placed on bare earth or on an impervious surface with or without leachate collection or other management features. Assumptions about the carcass pile design, management, and FMDv releases are discussed in Section 2.3 and Section 2.4.

2.2.3 Transportation

A semi-quantitative evaluation of chemical and microbial releases and potential exposures from transportation is presented in the assessment for natural disasters (USEPA 2017). That evaluation found a very low (7.1E-05) likelihood of materials in carcasses or carcasses themselves being released as a result of an accident during transit to an off-site management facility. In addition, mitigation requirements and standard practices (e.g., the use of truck bed covers and liners) greatly reduce non-accident releases from trucks in transit. These conclusions are further supported by an assessment conducted by the University of Minnesota's Center for Animal Health and Food Safety (UM CAHFS) (2014). In their assessment of risks of transmission of FMD by moving swine and cattle carcasses from an FMD-infected premises to a disposal site, UM CAHFS found that risk of infection for susceptible swine and cattle associated with transport of carcasses is (1) negligible if a standard rendering truck (tailgate sealed and tarp cover) is used together with a sealable liner to contain carcasses, and (2) negligible to low if (a) a standard rendering truck is used without a bag or (b) a roll-off/dump truck with a bag are used. If trucks are uncovered or only a liner is used to minimize leaks from a truck, risks of spreading infection to other susceptible animals are likely to be moderate to high (UM CAHFS 2014).

Moreover, in the specific case of transporting FMD-infected carcasses, all associated exposures can be assumed negligible if workers adhere to USDA's (2014a) biosecurity standard operating procedure (SOP) for FMD response. Also, if carcasses are transported after 48 hours of temporary storage, the pH reduction associated with *rigor mortis* would further reduce the amount of viable virus available for release during transportation. Carcasses are also covered during transport to reduce the scattering of external virus particles (i.e., particles present on hair, skin, hooves, and other external surfaces) to the environment.

2.3 Exposure Assessment Assumptions

Where possible, this assessment uses assumptions that are consistent with those used in the assessment for natural disasters (e.g., design of storage pile and burial trench; USEPA 2017). This section identifies assumptions used for the FAD assessment that differ from or are in addition to those for the natural disaster. Table 2.5 summarizes the assumptions for the FAD outbreak scenario.

Table 2-5. Foreign Animal Disease Outbreak Scenario Assumptions[a]

Issue	Assumptions
Scale of Livestock Mortality	▪ The quantity of carcasses to be disposed is 45,359 kg (50 U.S. tons). ▪ For cattle, 45,359 kg would equal 100 animals if they each weighed 454 kg.
Livestock Types and Quantity	▪ ***Livestock category likely to be impacted by an FMD outbreak in the U.S. – cattle.***
Carcass Management and Post-Management Assumptions	▪ Seven carcass management options with documented use following large-scale livestock mortalities are considered. ▪ The assessment begins with placement of carcasses in an outdoor temporary storage pile, assuming temperatures between 50 and 90°F before movement to the management location. ▪ Exposures are assessed for releases of ***FMDv only*** from management units and from post-management processes that contribute to the ultimate fate of the virus. ▪ Off-site livestock carcass management options operate in compliance with facility permits designed to limit off-site releases to health-protective levels; hence exposures to releases from off-site facilities are not evaluated. ▪ At a minimum footwear, clothes, equipment, vehicles, and other objects that could act as fomites in areas designated as Infected and Contact Premises are disinfected after depopulation by workers who wear appropriate PPE[b] prior to exiting those areas.
Carcass Handling	▪ ***When handling presumptive FMD-infected livestock and their carcasses (e.g., loading and unloading carcasses from vehicles or into management units), workers use USDA/APHIS-recommended "Level C" protection (USDA 2014b) and, therefore, are not infected.*** ▪ Workers do not take home any items of clothing used during FMD control and eradication activities. ▪ Non-workers do not touch or otherwise contact carcasses or equipment used to transport or handle carcasses, and the public is excluded from work sites. ▪ Biosecurity zones and associated biosecurity practices required for FAD outbreaks are used according to USDA/APHIS recommendations (USDA 2013b).
Temporary Carcass Storage	▪ Workers move carcasses from the mortality location to an outdoor pile on bare earth where they stay for 48 h before transport to management locations. There is no leachate collection or retention system for the pile. ▪ ***The outdoor storage pile is covered with a tarp to control contact with insects, wild birds, and other scavengers. However, there may be times when the tarp is removed and the pile is left uncovered to allow for more carcasses to be added to the pile.*** ▪ Disinfection products are not applied to the storage pile or carcasses (USDA 2013d). ▪ For 100 cattle carcasses, the storage pile has a trapezoidal cross sectional shape that is 8 ft (2.4 m) wide at the base, 3 ft (0.91 m) wide on top, and 5 ft (1.5 m)

Issue	Assumptions
	high. With a total volume of 196 yd^3 (150 m^3), the length of the pile is 132 ft (40.3 m).
Depopulation	▪ ***To contain the outbreak, all livestock in the herd on the outbreak farm are culled.***
Repopulation	▪ ***The farm will not be repopulated with potentially susceptible livestock until the area is considered to be "FMD-free" (i.e., infection with FMDv unlikely), a minimum of 28 days.***
Hazard Types	▪ ***The concentration of viable FMDv is significantly reduced by rigor mortis and the associated reduction in pH within cattle musculature. All cattle in the storage pile pass through rigor mortis within the 48-h holding period. FMDv present in muscle tissue and other non-hardy compartments is therefore inactivated. However, some viable FMDv could remain in bone marrow, lymph nodes, and internal organs.*** ▪ Carcass management will release chemical and other microbial agents that are naturally present in healthy animals or products of carcass management activities (e.g., combustion products). Those releases are assumed to be the same as estimated for the natural disaster scenario (USEPA 2017).
Geographic and Spatial Issues	▪ All carcass management options are evaluated with the same spatial, geographic, meteorological, and other environmental characteristics assumed for the natural disaster assessment (USEPA 2017) with one exception: ***virus leaching to ground water is evaluated in this assessment for three soil types: sand, silty loam, and clay.*** ▪ The site location and regional factors do not preclude the availability or feasibility of any carcass management option. ▪ ***Uninfected cattle are located on neighboring farms.***

Abbreviations and acronyms: APHIS = Animal and Plant Health Inspection Service; FAD = foreign animal disease; ft = feet; FMD = foot and mouth disease; FMDv = foot and mouth disease virus; h = hour; kg = kilograms; km = kilometers; m = meter; PPE = personal protective equipment; USDA = U.S. Department of Agriculture; yd = yard.
[a] Assumptions in ***bold, italic type*** are specific to the FMD outbreak assessment; all other assumptions were used in the natural disaster assessment (USEPA 2017).
[b] Contact Premises are defined as premises with susceptible animals that could have been exposed to FMD, either directly or indirectly, including but not limited to exposure to animals, animal products, fomites, or people from Infected Premises. Areas characterized as Contact Premises will be considered part of the Infected Zone and the Buffer Zone (USDA 2014a).
Complete references are found at the end of the report.

2.4 Sources of FMDv Releases and Exposure Pathways

This section describes the sources of FMDv released to environmental media (i.e., air, water, soil) and exposure pathways for uninfected livestock. It also includes conceptual models for each of the quantitatively assessed management activities and options: temporary carcass storage and burial.

2.4.1 Temporary Carcass Storage before Transportation

For the hypothetical FAD outbreak assessed in this report, the first action after euthanasia is to pile carcasses in a temporary storage area on the ground with strong tarps covering the pile and anchored firmly into the ground (USDA 2005). In an actual FMD outbreak, livestock might be herded to a burial trench or the area surrounding a compost windrow before euthanasia, allowing immediate placement with minimal handling. For this exposure assessment, however, on-site storage for 48 hours (2 days) is assumed for all management options. Figure 2.1 summarizes the conceptual model for the temporary carcass storage pile. It traces exposure pathways from the storage pile to livestock on farms near the outbreak farm or outside the FMD response area.

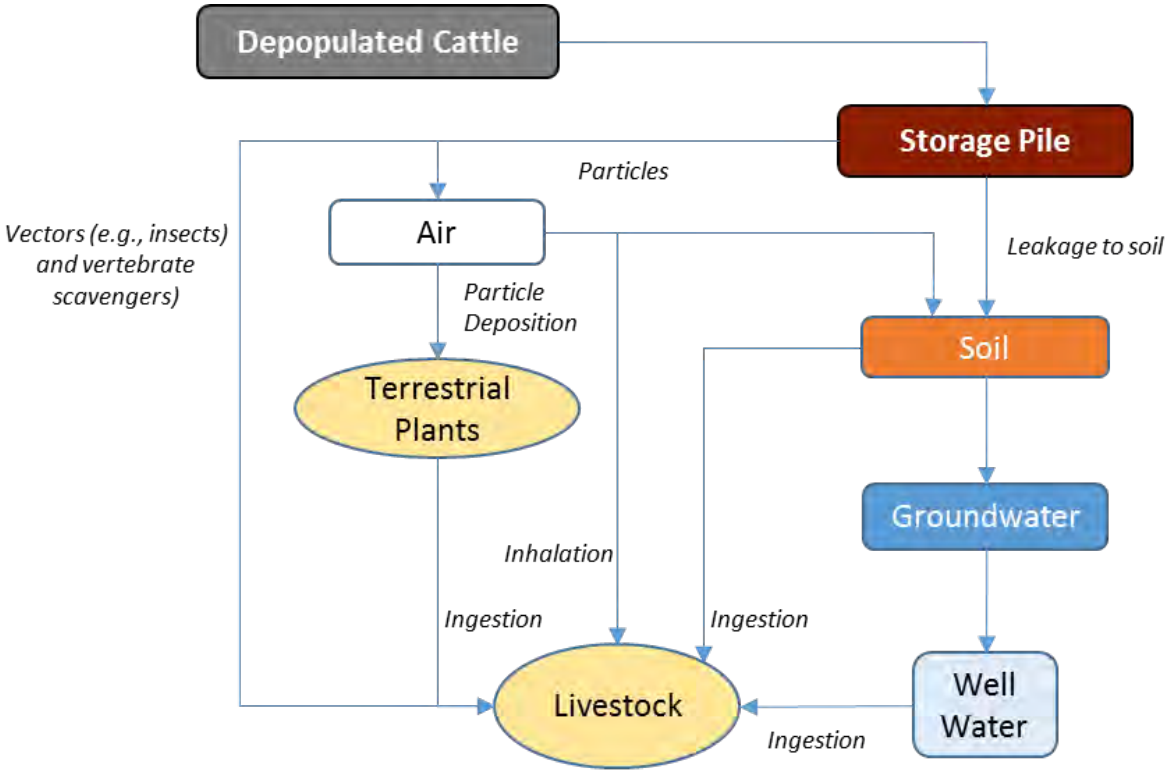

Figure 2-1. Conceptual model for exposure pathways from temporary carcass storage.

A temporary storage pile is likely to be uncovered for short periods, as when the tarp is removed or adjusted to accommodate additional carcasses. If the storage pile is uncovered, FMDv particles on the surfaces of carcasses can be released to air and transported beyond the FMD response area via wind. Neighboring livestock could either inhale the particles directly or ingest the particles after they deposit to terrestrial plants and soils, which cattle also ingest while grazing (Herlin and Andersson 1996; Gloster et al. 1981; Sorensen et al. 2000).

Liquid leaching from the storage pile is assumed to percolate down through soil toward ground water. Water from a ground water well off-site could be used for providing drinking water for neighboring livestock that have not been culled as part of the response effort.

Finally, vertebrate scavengers (e.g., birds, feral swine, rodents) and flying insects might spread the virus to other susceptible species after contact with FMDv-infected cattle carcasses in the temporary storage pile (USDA 2013b, 2013c).

2.4.2 On-site Burial

Figure 2.2 is the conceptual model for the on-site burial of FMD-infected carcasses. In this management option, livestock carcasses are placed in an unlined, excavated pit or trench in a suitable location on site. The carcasses are covered with 6 feet (ft; 1.8 m) of clean fill including 3 ft (0.9 m) of soil mounded over the site starting at ground level (USDA 2005). This soil cover will flatten over time as the carcasses lose fluids and other mass during decomposition. Although access to the site is not restricted, it will not be used in the relatively near future for crop farming or raising livestock; it will be seeded over for soil stabilization.

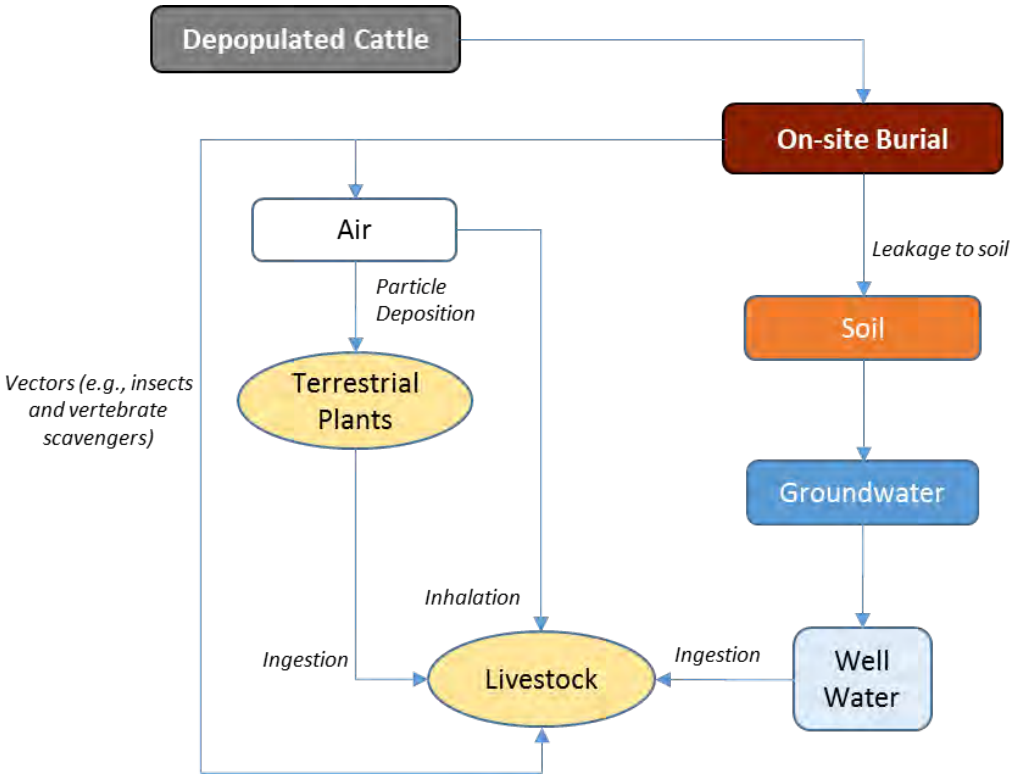

Figure 2-2. Conceptual model for exposure pathways from on-site burial of livestock carcasses.

As the carcasses decompose, rapidly at first (over months) with the remainder decomposing more slowly (over years), particles could diffuse upward though the soil cover to aboveground air. However, with the amount of soil cover placed on the burial trench (6 ft), it is unlikely that FMDv particles could travel through the soil cover and be released to air. Thus, exposure after burial via air is considered negligible.

In the burial trench, FMDv particles can leach with carcass fluids and with rainwater permeating through subsurface soils to ground water. If ground water is used to provide drinking water for cattle outside the FMD-response area, a complete exposure pathway exists that might not be

negligible. As discussed in Section 2.1, changes in pH (i.e., <6.0) associated with *rigor mortis* are expected to inactivate virus in muscle tissue while the carcasses are in the storage pile and before being placed in the burial trench. Viable virus can survive in bone and other tissues. Therefore, the concentration of infectious virus particles present in leachate released from the burial trench is expected to be lower than the concentration of infectious particles present in leachate released from the storage pile. Virus particles in buried carcasses will naturally decay (i.e., lose integrity and inactivate) over time. Based on the estimated rate of biological decay (see Section 3.1.2; estimated from data reported in Schijven et al. [2005]) the viable viral load would decline by at least 95% within a month, and none is expected to survive more than a year. Therefore, exposures from on-site burial of carcasses are evaluated qualitatively in relation to the exposures quantified for storage pile leaching.

2.4.3 Summary of Exposure Pathways for Livestock

Table 2.6 summarizes FMD exposure pathways for the temporary storage pile, which precedes all of the seven livestock management options, and for burial.

Pathways with quantitatively estimated exposures are indicated with bold type and footnote "a" in Table 2.6. Other pathways that are not assessed quantitatively are indicated by endnotes “b” and “c” in Table 2.6.

Table 2-6. Livestock Exposure Pathways for Livestock Carcass Management

Exposure Source	Carcass Management Options	
	Temporary Storage Pile	Burial
Air Inhalation	**1) Air**[a]	1) Air[b]
Direct Ingestion	**2) Air → Plants**[a]	2) Air → Plants[b]
Incidental Ingestion	**3) Air → Soil**[a]	3) Air → Soil[b]
Incidental Ingestion	**4) Air → Surface water**[a]	**4) Air → Surface water**[a]
Ground-water Ingestion	**5) Leachate → Ground water**[a]	**5) Leachate → Ground water**[a]
Vectorborne Transmission	6) Airborne vectors → Livestock[c]	6) Airborne vectors → Livestock[b,c]

Acronyms: SW = surface water
Notes: **Bold type** means quantitative methods will be used for exposure assessment.
On-site means inside the Infected Premise of the hypothetical farm. Off-site means beyond the Infected Premise, potentially on other farms. “—“ means no pathways identified
[a] Quantitative methods will be used for exposure assessment.
[b] Exposures assumed to be negligible.
[c] Pathway will be described qualitatively; quantitative modelling approaches not available.

3. Exposure Estimation

Section 3.1 describes the approaches used to estimate releases of FMDv to air and to soil for all carcass management exposure scenarios, including those scenarios evaluated as part of the uncertainty analysis. Section 3.2 describes the modeling methods employed for specific environmental media for these scenarios.

3.1 Estimation of FMDv Releases

As illustrated in the conceptual models in Section 2.4, FMDv particles could be released from carcasses: (1) to air during handling and temporary storage and (2) to soil via leachate from the temporary carcass storage pile and from the unlined burial trench. Estimates of these releases are needed to quantify exposure of susceptible livestock.

In this report, all exposure estimates are reported in units of FMDv $TCID_{50}$ values to allow comparison with available infectious dose data (see Section 2.1). The $TCID_{50}$ is a method of detection and quantification of the viral loading in a clinical or environmental sample. Much of the recently published measures (e.g., past two decades) of viral load in environmental or veterinary samples are reported as $TCID_{50}$ /mL. For this assessment, data reported in units of $TCID_{50}$ per unit volume or mass of material are used if reported; if PFUs are reported, they are not converted to corresponding $TCID_{50}$ values.

3.1.1 Air

Releases of FMDv particles to air as aerosols could occur from handling the carcasses and the temporary storage pile when uncovered to add or to remove carcasses. Aerosols are particles consisting of aggregated smaller particles (e.g., virus, skin cells, dust) together with some liquid droplets. Aerosols are small enough to have a high surface area to mass ratio so that they remain suspended in air for some time before aggregating further and falling to the ground. An aerosol can be characterized by a distribution of particle sizes and each aerosol particle can contain one to many viral units.

Virus release rates in aerosol particles

Carcass handling and temporary storage is assumed to take place over the course of 2 days (48 hours total). The temporary storage pile is covered with a tarp for no more than 48 hours (Day 1 and Day 2) before carcasses are moved to their respective management location. The estimated aerosol with virus release rate covers both carcass handling (e.g., movement to the temporary storage pile) and storage. Separate release rates are not derived for the two activities because virus release data are available only for live animals.

Infected carcasses have surfaces that can carry FMDv (i.e., act as fomites) during handling and storage. Aerosolized viable virus could be released from FMD-infected skin, hooves, lesions, or hide during carcass handling or placement in the storage pile (Sellers and Parker 1969; Dillon 2011). Identified mechanisms for the release of infectious aerosols from carcasses include exposure to moving air or mechanical abrasion (Dillon 2011). Neither our 2016 literature review nor the literature reviewed by Dillon (2011) identified any measured emissions data for FMDv released from cattle carcasses infected with FMDv. As a result, the release of FMDv from cattle

carcasses is estimated for handling and placement on the storage pile using modeled releases of FMDv from live cattle.

The aerosol release rate is selected from reported outputs of the Sorensen et al. (2000) virus production model, which described the rate of release of FMDv aerosol for live infected cattle relative to day of clinical disease. This model was calibrated using reported and modeled data (Sellers and Parker 1969; Donaldson et al. 1970) for live cattle infected with FMDv. The model also included an extrapolation component when data were not available for the desired number of days post-infection. The highest estimated release was 5.1 $\log_{10}$ $TCID_{50}$ (1.26E+05 $TCID_{50}$) per cow per 24-hour period (Sorensen et al. 2000), which is used as the base-case aerosol release rate for FMD-infected cattle carcasses. Aerosol release rates from carcasses should be lower than from living animals that breathe in and out, exhaling aerosolized FMDv particles with each breath. Carcasses and living cattle might release FMDv particles from external surfaces (e.g., adsorbed to hair and skin, from mucous-covered surfaces).

Variability in the viable FMDv particles in aerosol releases from handling and placement in the storage pile could be affected by the same elements associated with variability in viable FMDv particles in aerosol released from live, breathing FMDv-infected animals: FMD strain differences, host breed, stage of infection, ambient environmental conditions (e.g., relative humidity) that could favor viability of virus (Sellers and Parker 1969; Sellers et al. 1971; Alexandersen et al. 2003). Additionally, aerosol release rates could be affected by the carcass location in the storage pile (e.g., more or less contact with potential air currents or mechanical abrasion). As noted earlier, the selected aerosol release rate was developed from data on live, infected, breathing cattle, and therefore, it is likely to overestimate releases from hides or carcasses in a pile. Because of its uncertainty and likely bias, the estimated aerosol release rate will be varied to examine the sensitivity of exposure estimates to release rate (see Section 4.3).

Particle size and FMDv distribution for aerosol source release

In addition to aerosol particle release rate (with virus in particles), air dispersion modeling for the exposure assessment requires information about the size distribution and mass of airborne particles and the density of viral units in the aerosol. The assessment assumes that FMDv-containing particles from carcass management activities are a mixture of ambient aerosolized biological and non-biological matter (e.g., FMDv, feed, dust, skin, feces). No data have been identified that reported the particle size distribution for exhaled aerosols associated with FMDv-infected cattle, healthy cattle, or the possible aerosol particle size distribution associated with cattle carcasses.

The FMDv-containing particles in the released aerosols are assumed to have the same particle-size distribution as that reported for two live cattle farms in the Netherlands (n = 51 and 104 cattle, respectively; Lai et al. 2014). An aerosol particle mass density of 1 gram (g) per cm^3 was assumed for modeling.

Gloster et al. (2007) found no difference in the airborne particle-size distribution associated with healthy pigs compared with the airborne particle-size distribution from FMDv-infected pigs in a confined space. FMDv-containing aerosol particles released from the pigs associated with the ambient particle load (Gloster et al. 2007). Therefore, the particle-size distribution associated with aerosols from the surfaces of FMDv-infected cattle carcass is assumed to be the same as the

particle-size distribution from non-FMDv-infected live cattle. Gloster et al. (2007) found FMDv infectivity to be generally evenly distributed in airborne aerosol particles measured in the confined air-space with the FMDv-infected swine. FMDv infectivity (as measured in $TCID_{50}$ units) in aerosol particles was evenly spread over particles of diameter < 3 µm, 3 to 6 µm, and > 6 µm. The following particle size and mass fraction distribution is used for air dispersion modeling in this assessment:

- 0.25 to 1.0 µm: 2.5%
- 1.0 to 2.5 µm: 2.5%
- 2.5 to 10 µm: 36.25%
- 10 to 32 µm: 58.75%

Biological decay

Aerosolized FMDv is assumed to inactivate over time outside of the host body, which is called biological decay. Donaldson and Ferris (1978) reported a biological decay rate of 50% per hour for FMDv in bovine fluid medium FMDv. Both Sorensen et al. (2000) and Garner et al. (2006) used that biological decay rate in their models of risks from wind-borne FMDv. In this assessment of carcass management options, that decay rate also is used for airborne FMDv.

In air dispersion models, the decay rate is often reported as the rate of particle loss per second. Thus, 0.5 $\log_{10}$ loss of FMDv particles per hour was converted to the percentage of FMDv particles lost per second. The biological decay rate for FMDv equals 1.90E-4 per second or 0.019% per second.

Because the rate of biological decay has a high level of uncertainty, it is varied in the uncertainty analysis conducted as part of this assessment.

3.1.2 Subsurface Soil

A Microsoft® Excel™ workbook was developed to estimate concentrations of FMDv reaching ground water via leaching from the temporary storage pile. Leaching from the burial trench is evaluated relative to leaching from the storage pile. Exposure to neighboring cattle occurs when the cattle receive drinking water from an affected well.

Leachate Volumes

Within hours after death, carcasses can release free fluids (e.g., contents of intestines, urine, fluids in lungs) and within days additional fluids are released due to decomposition. Fluids that seep into the ground as a leachate may eventually reach ground water. Some constituents that remain dissolved in water and that do not adsorb to soil particles (e.g., chloride ions) will reach ground water as the leachate from reaches ground water. Chemicals and particles in leachate that have a strong tendency to sorb to soil particles, on the other hand, will be retarded relative to water transport to ground water owing to adsorption to and desorption from soil particles.

The volume of leachate loaded to the surface layer of soils immediately under a temporary storage pile is estimated from data reported in Young et al. (2001). Assuming that the quantity of fluid released over the first week after mortality is released evenly over time (i.e., estimate for one week is divided by 7 days to estimate daily release), approximately 10.7 liters (L) of leachate

would be produced per 454 kg carcass per day.[9] For 100 carcasses, the total estimated volume of leachate from the temporary storage pile is 1,070 L per day. The actual amount of leachate released per carcass per day will vary depending on the size and condition of carcasses, ambient temperature, and other factors. Thus, the volume of leachate released per carcass is varied as part of the uncertainty assessment.

Virus load

Alexandersen et al. (2003) collected FMD strain-specific data on the maximum recorded virus titer in, and volume or weight of, various secretions and excretions from FMD-infected cattle including blood or serum, feces, and urine. UM-CAHFS (2014) and Gale (2002) also reviewed virus titer data from various carcass tissue compartments including skeletal muscle, heart muscle, skin/hides, lymph nodes, and kidney. Secretions or excretions with relatively high total virus loadings include feces (approximate loading of 1E+05 $TCID_{50}$ per gram) and urine (approximate loading of 1E+05 $TCID_{50}$/mL) (Kitching 2002). Major internal tissue compartments include the blood (approximate total loading of 1E+11 PFU per carcass) and muscle (approximate total loading of 1E+07 PFU per carcass) (Gale 2002; Alexandersen et al. 2003; UM CAHFS 2014). These authors reported load in various measures, such as $TCID_{50}$, PFU, and others reported from various tissue-culture types. While there is no agreed upon value to relate $TCID_{50}$ to PFU (Gale 2002), UM CAHFS (2014) assumes that one PFU equals about 1.4 $TCID_{50}$ for FMDv based on Alexandersen et al. (2003) and Donaldson and Ferris (1978); 1 $TCID_{50}$ equals approximately 0.7 PFU. For this assessment, all measurement units are assumed to be equivalent to 1 $TCID_{50}$ unit. UM CAHFS (2014) estimated that the total FMDv in one cattle carcass could be 1 E+06 PFU/gram, which would equal 1 E+09 PFU/kg or 4.54 E+11 PFU/carcass where one carcass weighs 454 kg. The number of $TCID_{50}$ values per carcass would be somewhat higher.

The initial virus load is included in the uncertainty analysis for this assessment because of the limited information on which to base an estimate and because of the potential for the virus load to vary substantially among cattle in the same herd at the time the animals are culled.

Biological decay

After the leachate is released to the soil from the carcasses in a temporary storage pile, the concentration of viable (i.e., infectious) FMDv is continually reduced over time by biological decay without a living host animal. For this assessment, the biological decay rate estimated for in-ground decay is applied from the time the leachate is released from the carcasses until it reaches ground water. The concentration of viable virus particles per liter water when the FMDv particles start to break through to ground water is calculated.

For burial, biological decay can be assumed to continue after the carcasses are moved from the storage pile to the burial trench. After burial in the summer, the decay rate might be slower than when carcasses were above ground due to the cooler and more stable temperatures in the burial trench. In winter, the temperature of buried carcasses and the surrounding subsurface soils (e.g.,

[9] Although not reported by Young et al. (2001), ambient temperatures were likely between 40 and 70°F in the spring, summer, and fall of 2001 in Wales and England where the outbreaks occurred.

11°C or 52°F) might be well above the freezing ambient air temperatures possible across much of the United States.

No data are available to describe the decay rate of FMDv in cattle carcasses under any defined conditions. The assumed first order biological decay rate in the source for the base case is 0.12 per day (1.4E-06 per second), which is based on measured biological decay of FMDv in cattle liquid manure at 17°C of 0.05 $\log_{10}$ $TCID_{50}$ per day (Schijven et al. 2005; Table 1). These rates represent the fraction of viable virus particles that become unviable per unit time. Biological decay is included in the uncertainty analysis for this assessment because of the limited information on which to base an estimate, as well as the potential for actual rates to be affected by environmental conditions.

Concentration in leachate

The resulting assumed pathogen loss of FMDv to leachate from one carcass in the temporary storage pile for the base case is 9.4E+08 $TCID_{50}$ per day. Derivation of this value takes into account both the release of FMDv to leachate (i.e., loss per day; 0.1) and the biological decay (i.e., loss per day; 0.12). The concentration of FMDv in leachate produced by carcasses in the burial trench would be lower than this because all virus in the cattle musculature is inactivated by *rigor mortis* during the two-day storage prior to burial. If the carcasses are placed in the trench immediately after death without temporary storage, the virus loading would be the same as the storage pile.

3.2 Fate and Exposure Estimation Methods

The methods described in this section simulate processes that occur between FMD source locations and the locations where live cattle are exposed. These processes include dispersion of FMDv in air, deposition from air to plants and soil ingested by grazing cattle, and leaching from the temporary storage pile and burial trench to ground water. Each of these fate and exposure processes requires some time, and so should include the estimates of biological decay.

3.2.1 Air Dispersion Modeling

Several models have been developed to simulate air-borne spread of FMDv over short and long distances between the time a herd is infected and the time when it is reported and animals are culled (Gloster et al. 1981, 1982; Moutou and Durand 1994; Sorensen et al. 2000; Mikkelsen et al. 2003; Garner et al. 2006). The current assessment differs from those assessments in that only the infectivity of animals that have just been euthanized (culled) is considered (i.e., the virus is no longer replicating within animals nor are any more animals in the herd infected after the outbreak is recognized and each animal is culled).

Dispersion of airborne virus particles is modeled with the American Meteorological Society (AMS)/USEPA Regulatory Model Improvement Committee Model (AERMOD) (version 14134) for air dispersion.[10] AERMOD calculates air concentrations and rates of wet, dry, and total deposition to the ground resulting from FMDv released to air from an area source[11] with

[10] Complete documentation of AERMOD and related tools, including AERMOD, AERMET, and AERSURFACE, is available at https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models.

[11] An "area source" is used with AERMOD and other air dispersion models when emissions emanate from an area instead of a "point source."

horizontal dimensions equal to the assumed size of the pile (i.e., 96.7 m^2 for 100 cattle). The assessment assumes emissions originate at the height of the pile. The assessment also assumes that FMDv is emitted from the storage pile at a continuous rate of 116 $TCID_{50}$ per second (also equivalent to counts per second and derived from the 24-hour aerosol release rate of 1.3E+05 $TCID_{50}$ from Sorensen et al. 2000). *Rigor mortis* is not relevant to this release rate because all particles are released from the surfaces of the animals. Once emitted, FMDv inactivates at a rate of 0.019% per second (estimated from biological decay rate of 0.5 $\log_{10}$ FMDv particles per hour reported by Donaldson and Ferris, 1978, as cited by Garner et al., 2006, and Sorensen et al., 2000).

AERMOD calculates average hourly air concentrations and deposition rates for each hour during the full year of meteorological data (described further in USEPA 2017), with the source emitting continuously at a constant rate. All estimated air concentrations are in units of $TCID_{50}$ per cubic meter (m^3), and deposition rates are in units of $TCID_{50}$ per m^2 per hour. Concentrations and deposition rates are calculated at 304 locations on a radial grid centered on the source: each of the 16 radial lines is separated by 22.5° and includes 19 locations (at 0.1 km intervals from the source to 1 km, and at 1 km intervals thereafter to 10 km).

Because carcass storage is assumed to last 48 hours, the hourly results are processed to find the highest 48-hour average air concentrations during the year for each location. For comparison purposes, all results are also recorded for 24-hour and 1-hour averaging periods. For deposition, the results are processed to find the highest 48-hour total deposition at each location. Separate results are obtained for wet, dry, and total deposition at each location.

3.2.2 Concentrations of FMD in Surface Soil

The deposition results discussed in the previous section (3.2.1) are used to calculate concentrations of FMDv in surface soil. Deposition processes in AERMOD include both wet and dry deposition based on the meteorological data for the 48-hour period resulting in the highest deposition to ground level. Before the soil concentrations are calculated, a first-order decay equation is used to estimate the amount of viable virus remaining at the end of the 48-hour deposition period. Equation 3.1 calculates the amount of viable virus remaining after a specified number hours of decay.

$$vDP_{(t)} = vDP_{(0)} * e^{-\lambda * t} \qquad \textbf{(Eqn. 3.1)}$$

where:

$vDP_{(t)}$	=	*Viable* virus particle deposition ($TCID_{50}$ per m^2 per hour) at time = *t* hours
$vDP_{(0)}$	=	*Viable* virus particle deposition from AERMOD ($TCID_{50}$ per m^2 per hour) at time t = 0
λ	=	Fraction of viable virus particles inactivated per hour (i.e., biological decay, 5.0E-03 per hour in air).
t	=	Time, number of hours of decay (t = 1 to 48), hours

Equation 3.1 is used to estimate the amount of viable FMDv present at the end of the 48-hour deposition event. The decay rate (λ) is the rate per second discussed in Section 3.1.2 converted to an hourly rate. Virus particles deposited during the first hour have 47 hours (t = 47) of decay before the end of the event. Virus particles deposited during the second hour have 46 hours (t = 46) of decay. These calculations continue for each hour of the event until no decay is applied to the final hour. The hourly viable virus deposition amounts are totaled, see Equation 3.2, for the count of viable FMDv particles at the end of the 48-hour event.

$$\sum_{t=0}^{47} vDP_{(t)} \qquad \textbf{(Eqn. 3.2)}$$

In the days following the 48-hour event, cattle continue to graze in the deposition area, and the amount of viable virus decreases each day with continuing decay. Equation similar to Equations 3.1 and 3.2 are used to estimate the amount of viable FMDv remaining each day for 21 days after deposition ends. The daily estimates are used to calculate the total FMDv ingestion through the 21st day. Day 21 was chosen as the endpoint of estimating ingestion exposure because by that time decay has reduced the viable FMDv to the point that daily incremental exposure is less than 1%.

Concentrations of FMDv in soil are calculated using Equation 3.3 (below) based on USEPA's (2005) *Human Health Risk Assessment Protocol for Hazardous Waste Combustion Facilities* (HHRAP). In Equation 3.2, the total 48-hour deposition of viable virus particles is mixed with the surface soil layer. The resulting estimate, *Cs*, is the concentration of $TCID_{50}$ per kilogram bulk soil at the deposition location.

$$Cs = [vDp_{(t)}] / (Zs * BD) \qquad \textbf{(Eqn. 3.3)}$$

where:

Cs	=	Concentration of viable virus in surface soil, from deposition, $TCID_{50}$/kg
$vDp_{(t)}$	=	Total viable particle deposition over 48 hours, $TCID_{50}/m^2$
Zs	=	Soil mixing zone depth (m)
BD	=	Soil bulk density, kg/m^3

For the base case, soil parameter values are HHRAP default assumptions. Specifically, HHRAP assumes that deposited particles mix with the top 0.02 m (0.79 inches [in]) soil layer. HHRAP also provides default assumptions for bulk-soil density at 1,500 kg per m^3 (surface soil, unsaturated).

Losses from soil due to erosion and leaching are assumed to be insignificant during the 48-hour deposition period.

3.2.3 Concentrations of FMD in Feed

HHRAP (USEPA 2005) provides methods to estimate chemical exposures of livestock farmed for beef, dairy, poultry, eggs, and pork products. Included in the HHRAP methods are equations

to estimate contaminant levels in livestock feed. These are adapted for this project to estimate the amount of viable virus present in vegetation (assuming grasses and herbs) grazed by cattle.

Equation 3.4 uses the wet and dry deposition rates from AERMOD, corrected to account for biological decay following deposition as described in Section 3.2.2, to estimate the amount of viable virus on plant surfaces (i.e., grasses and herbs grazed by cattle, also called "forage") at the end of the 48-hour deposition period.

$$Cp = [vDpd + (vDpw * Fw)] * Rp * Kp / (kp * Yp) \qquad \textbf{(Eqn. 3.4)}$$

where:

Cp	=	Infective FMDv on aboveground vegetation due to particle deposition, $TCID_{50}$/ kg plant, dry weight (DW)
vDpd	=	Viable FMD particle dry deposition from AERMOD, $TCID_{50}/m^2$
vDpw	=	Viable FMD particle wet deposition from AERMOD, $TCID_{50}/m^2$
Fw	=	Fraction of wet deposition that adheres to forage plant surfaces (unitless), HHRAP default of 0.6
Rp	=	Interception fraction of the edible portion of plant tissue for the plant type, unitless, HHRAP default of 0.5 for forage
Kp	=	Plant surface loss coefficient, 0.1 per event (see below)
Yp	=	Yield or standing crop biomass of the edible portion of the plant (productivity) (kg DW/m^2), HHRAP default of 0.24 for forage

Default values for the parameters *Fw*, *Rp*, and *Yp* are documented in USEPA (2005). The plant surface loss coefficient (*Kp*) accounts for loss of particles from plant surfaces with time due to wind removal, water removal, and growth dilution. HHRAP recommends a default value of 18 per year. Converted for the 48-hour event period used in this assessment, the *Kp* value is 0.10 per exposure event. The HHRAP default is based on half-life data for a variety of contaminants on plant surfaces reported by Miller and Hoffman (1983). These data are assumed to represent the half-life of virus particles sticking to plant surfaces.

The amount of viable FMDv remaining on aboveground vegetation is estimated each day for 21 days after the end of the 48-hour deposition event. The daily estimates are used to account for ongoing decay as cattle graze in the deposition area following the end of the deposition event.

3.2.4 Concentrations in Ground Water

If there is no barrier between the carcasses in the storage pile and the ground below, FMDv particles in carcass leachate could seep downward through the unsaturated soil zone until reaching ground water. Exposure could occur if ground water drawn from a well downgradient from the carcass management location is used to provide drinking water for healthy cattle. The nearest cattle would be at a distance from the source, because all cattle at the affected farm, and

possibly other farms in the response zone, would be culled to contain the outbreak (see Section 2.2).

Two steps are used to evaluate the fate and transport of FMDv particles in the soil-to-ground water pathway. First, the Virulo model developed by Faulkner et al. (2002a) is used to model the movement of virus particles downward through the unsaturated soil zone, and the probability that they reach ground water. Virulo does not estimate the amount or concentration of virus particles reaching ground water and it does not model the fate of viruses after they reach the ground water. In addition, it does not include biological decay.

In the second step, simple spreadsheet calculations are performed to estimate FMDv concentrations in well water with the effects of biological decay and dilution. These calculations overestimate FMDv in well water because they do not include the complex sorption-desorption dynamics addressed in the Virulo model. However, comparing the leachate and well water concentrations provides a *conservative* estimate of the reduction in concentration and potential exposure. In addition, the base case results can be compared to results calculated with varied assumptions (e.g., soil depth, numbers of carcasses) to examine how the varied factors individually affect potential exposures.

Leaching to Ground Water Analysis with Virulo

Virulo (Faulkner et al. 2002a, b) is a screening model that uses probabilistic Monte Carlo simulations to predict virus transport and survival through soils. It is based on a conceptual model that simulates several natural processes and forces that influence water flow and virus transport in variably saturated soils. The model uses built-in distributions of physical, biological, and chemical factors and a set of default properties virus and soil types. The documentation for the Virulo model lays out the limitations of the model, “In instances where the ground-water system in question is connected to potential virus sources by karst, fractured rock, gravel, or a soil exhibiting preferential flow, the system will be classified as high risk. In other cases the assessment process will benefit from prediction by mathematical modeling” (USEPA 2002a). For those cases where mathematical modeling is appropriate, important assumptions in the Virulo modeling approach are identified below.

- Water flow is one-dimensional, vertical, and uniform (i.e., the soil is homogenous with respect to geochemistry and hydraulic properties), although degree of soil saturation varies.
- Flow has reached steady-state.
- Water moves downward under the force of gravity only (there are no abrupt changes in capillary pressure in the soil).
- Water content is variable, simulating instantaneous and random recharge from precipitation (rather than cyclical wetting and drying).
- There are no preferential flow pathways (e.g., root pores).
- Virus transport is simulated by linear absorption-desorption processes typical of dissolved chemicals rather than by colloidal filtration.

The Virulo model includes “instantaneous” equilibrium, and therefore does not include time or a biological decay rate.

Virulo output is expressed as the probability that virus particle attenuation *does not* equal or exceed a target level of attenuation by the time the leaked fluids with virus particles "break-through" to ground water. The default attenuation target is *99.99%* (i.e., fails to achieve a four-fold log10 reduction in virus concentration). The user can choose the attenuation target level, values for various soil and virus properties, and the number of Monte Carlo simulations.

In the Virulo documentation (Faulkner et al. 2002a), USEPA provides example results of a Monte Carlo simulation for polio virus attenuated by 1 m of soil between the release source (breach of septic system) and ground water for sand, silt-loam, and clay. The example results use model default values, including a 4 log10 (i.e., 99.99%) attenuation target. The results are summarized below for the three soil types.

- **Sand --** The probability of failure to attain 99.99% reduction attenuation was 22 simulations divided by the number of simulations (5697), or 0.39% failure.
- **Silt-loam --** Six simulations out of 2 million (i.e., 0.0003%) failed to reach 99.99% attenuation.
- **Clay --** There were no failures to reach 99.99% attenuation out of 9 million runs (Faulkner et al. 2002a).

These findings suggest that polio virus has a low probability of reaching ground water at a minimum depth of 1 m with less than 99.99% reduction, particularly at sites with silty-loam or clay soils.

For this assessment, Virulo was used to examine attenuation of FMDv attenuation with 1 to 8 m depths of silty loam. In addition to the default attenuation target (i.e., 4 log10), simulations were run for attenuation targets of 5 log10 through 8 log10 at intervals of one order of magnitude. The more stringent attenuation targets were included because higher viral loading rates at the surface would require a higher target attenuation to reach a specified concentration (e.g., based on infectious dose and cattle water ingestion rates) entering ground water.

Default inputs for FMDv are not available in Virulo. As a substitute, simulations were run using a default soil/liquid partition coefficient (K_d) value for another member of the Picornaviridae family, Echovirus. Specifically, the estimates were made with the Echovirus-clay K_d value of 4.5E-04 m^3/g (or 453.5 L/kg). For comparison, the default K_d values for Echovirus in silty-loam is similar (442 L/kg), and for K_d for Echovirus in sand is higher (744 L/kg). Figure 3.1 summarizes the results.

Figure 3.1 shows that between 40 and 50 out of 10 million simulations failed to achieve attenuation of 99.99% (i.e., 4 log10). More simulations failed to achieve the higher attenuations targets (as shown in Table 3.1). Notably, the probability (or risk) of failing to reach the attenuation target is similar with soil depths ranging from 1 to 8 m, and the estimated number of failures do not necessarily increase with soil depth. This indicates that the estimates may be more sensitive to parameters varied in the Monte Carlo simulations than to soil depth.

The simulations with Virulo indicate that FMDv released from the temporary carcass storage pile or burial trench will have a very low probability of reaching ground water when the depth of the ground water is at least a meter. These results alone overestimate the likelihood of exposure to

cattle because Virulo does not address dilution in ground water or biological decay in either the vadose zone or ground water. These two factors examined in the sections below.

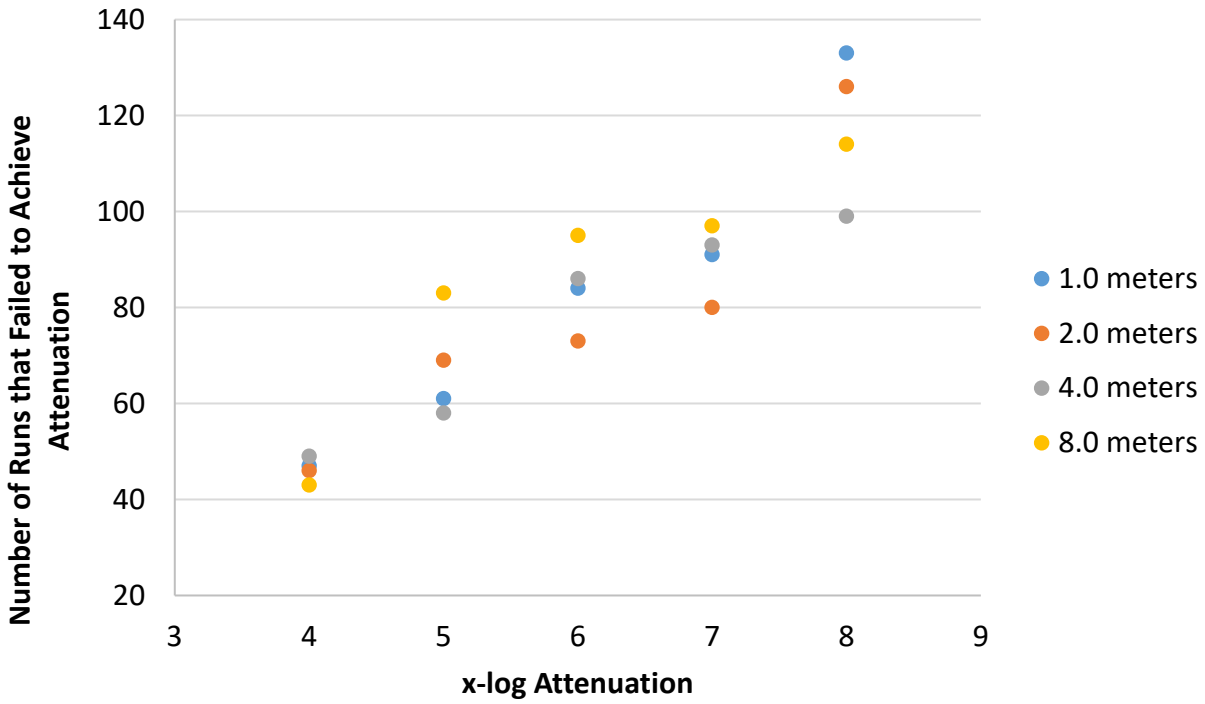

Figure 3-1. Number of Monte Carlo simulations (out of 10 million) that failed to reach attenuation target at four soil depths.

Table 3-1. Estimated risk of FMDv Breakthrough to Ground Water at Soil Depths of 1-8 m

Target Attenuation (%)	Number of 10-fold Reductions	Low-end Risk of Failing to Achieve Target Attenuation	High-end Risk of Failing to Achieve Target Attenuation
99.99	4	4.0E-06	5.0E-06
99.999	5	5.8E-06	8.4E-06
99.9999	6	7.2E-06	9.3E-06
99.99999	7	8.0E-06	9.5E-06
99.999999	8	9.8E-06	1.3E-05

Dilution and Biological Decay Calculations

This section describes simple calculations to examine the extent to which dilution and biological decay processes, individually and combined, reduce concentration of FMDv in a downgradient well used to provide drinking water for cattle. Because the estimates presented in this section do not include the complex processes simulated by Virulo, the difference in estimated concentrations at the carcass storage pile and the well represents a conservative level of reduction in this exposure pathway. In addition, an uncertainty analysis with the base case estimate will examine how the level of exposure varies by soil type, soil depth, scale of mortality, and other factors.

Dilution Attenuation

After seeping into the ground beneath the temporary storage pile or burial trench, leachate is subjected to dilution and other physical, chemical, and biological processes that attenuate leachate constituents. To support regulatory analyses, USEPA (1996) created the USEPA Composite Model for Leachate Migration with Transformation Products (EPACMTP) to simulate dilution attenuation in both the unsaturated and saturate zones. In an application of this model, USEPA developed a set of dilution attenuation factors (DAFs), ratios of leachate concentrations at the source to the concentration in water at a downgradient well. With a DAF of one, a constituent concentration at the well would equal concentrations at the source. DAFs greater than one indicate dilution and attenuation the constituents before reaching the well.

USEPA developed the DAFs by running Monte Carlo simulations with EPACMTP and nationwide data sets for waste sites and hydrogeological parameters (USEPA 1996). Simulations were run with six well-placement scenarios that included well distances of 0 m, 25 m, or 100 m, or distances randomly selected from a distribution of nationwide data. The well's horizontal offset distance from the plume center line was randomly selected, either within the plume's width or half the width. Well depths were randomly selected from nationwide data for most scenarios.

Because sensitivity analyses determined that soil types and the size of the contaminated area have the greatest effect on the DAFs, USEPA developed DAFs for a sources ranging in size from 1,000 to 5,000,000 ft^2 (93 to 464,515 m^2). With further analysis, USEPA prepared a default nationwide DAF of 20 for sources up to 0.5 acres (0.2 hectares).

For this assessment, the DAFs produced using the EPACMTP Monte Carlo analysis are used to estimate $TCID_{50}$ concentrations in well water 100 m downgradient from a temporary storage pile or burial trench. Because DAF are sensitive to the size of the leachate source, the area of the storage pile was matched to the distribution of DAF values by size presented by USEPA (1996, Appendix E). For each source size, USEPA presented DAFs corresponding to the 85th, 90th, and 95th percentile of Monte Carlo simulations. Because USEPA based the default DAF on 90th percentile results, the DAFs for this assessment were based on the 90th percentiles as well. The DAF applies to leaching from the temporary storage pile with the base case (i.e., management of 100 carcasses) is 1,675. For comparison, the DAFs for storage piles with 1,000 and 10,000 carcasses are 201 and 24, respectively.

The EPACMTP modeling effort described above included simplifying assumptions that make the estimated DAFs conservative. For example, retardation due to absorption/desorption kinetics were excluded by assuming that soil and porewater concentrations are at equilibrium. In addition, chemical and biological degradation processes were not considered (USEPA 1996). Thus, the modeling approach is likely to overestimate chemical concentrations in ground water.

Biological Decay

The effect of biological decay on FMD exposure depends on the inherent biological decay rate of the virus, which may vary with changes in temperature, moisture, and other environmental conditions. As discussed in Section 3.2, leachate modeling this assessment uses an FMDv decay rate of 0.12 $TCID_{50}$ per day (1.4E-06 per second), which was measured by Schijven et al. (2005) in liquid cattle liquid manure.

The amount of decay also depends on the time elapsed between release from the storage pile or burial trench and ingestion by cattle. The time is, in turn, is determined by a number of site-specific factors including, (1) soil depth and type, (2) the downward velocity of the leachate in unsaturated soil before reaching ground water, (3) the horizontal ground water flow rate, and (4) the distance to the well. The data and assumptions in this assessment for each these four factors are discussed below.

With the estimated FMDv concentration in leachate, biological decay rate, and an estimated travel time to the well, the amount of viable FMDv in well water is estimated with formula similar to Equation 3.1.

Soil Depth and Type

Many states recommend or mandate minimum depths of unsaturated soil beneath carcass burial pits to protect ground water quality. These distances are as little as 1 ft (~0.3 m), but are more typically 3 ft (~1 m) or more (NABCC 2004). Based on this information, the default soil depth for this assessment is 1 m. To examine how soil depth affects exposure estimates, the assessment also includes depths ranging from 0.5 to 6.

The assessment includes three soil types (sand, silty-loam, and clay) with distinct characteristics (e.g., porosity). These soil types were included in the Faulkner et al. (2002a) example Virulo analysis with polio virus, described above, which showed that virus mobility differs by soil type.

Downward Velocity in Soil

“Average” downward water velocities (i.e., discharge velocity or apparent velocity), based on summaries provided by the USDA Natural Resources Conservation Service (USDA NRCS 2008) and the United Nations Food and Agricultural Organization (UN FAO 2006), are listed in Table 3.2 for sand, loam, and clay soils. To approximate the time of travel for a virus particle from the ground surface to the ground water, the depth of soil above the water table can be divided by these downward velocities, as shown in Table 3.2 for the base case depth of 1 m. These simple calculations overestimates the rate of travel for virus particles because they do not

account for absorption-desorption processes, which retard their movement as demonstrated by the Virulo simulations above.

Table 3-2. Average Downward Travel Velocities and Time to 1 m Depth in Unsaturated Soils

Soil Type	Average Downward Water Velocity (cm/day)	Average Time to Breakthrough (day)
Sand	100[a]	1.0
Loam	18[b]	5.6
Clay	2.5[c]	40

Abbreviations and acronyms: cm = centimeter; g = gram
Complete references are found at the end of the report.
[a] For sand, USDA NRCS (2008) lists > 49 cm/day and UN FAO (2006) lists 5 cm/hr (120 cm/day), while other sources suggest 1,000 cm/day possible for very coarse sand. Value of 100 cm/day used.
[b] For loam, USDA NRCS (2008) states 12 to 24 cm/day. Average of NRCS range used here.
[c] For clay, USDA NRCS (2008) lists 2.5 to 12 cm/day, while UN FAO (2006) lists 1.2 cm/day for clay; low end of NRCS range used here.

Ground Water Flow Rate

Ground water flow rate is one of the parameters varied in USEPA's (1996) Monte Carlo modeling to develop DAFs. Specifically, USEPA used a nationwide probability distribution of ambient ground water velocities, with 15th, 50th, and 85th percentile values of 53.2, 404, and 2883 m/yr, respectively. The 50th percentile (i.e., median) value is selected as the default ground water flow rate for this analysis.

Well Distance

As discussed above under Dilution Attenuation, the well distance assumed for this assessment is 100 m, which is the value associated with the USEPA DAFs presented in Table 3.2. It also is the minimum distance included in the AERMOD dispersion modeling. A distance of 100 m to the nearest well is a conservative assumption for the FAD outbreak scenario. State or local regulations in some areas will preclude siting a burial trench 100 m from a well. However, the minimum required distance is less than 100 m in several states (NABCC 2004). In addition, live, uninfected cattle are very unlikely to be kept as close as 100 m from the carcass management site (e.g., temporary storage pile). However, the cattle do not need to be at the well location to receive water from the well.

Using survey data, USEPA (1997) prepared a probability distribution of the nearest well distances. Only wells within 1 mile (1609 km) from a landfill were included in probability distribution. Considering only those wells, the chance of the nearest well being100 m or less from a landfill is approximately 10%. The 50th percentile distance is 427 m, and a distance of 1 km corresponds to approximately the 80th percentile. Although the proximity of wells to landfills is not necessarily representative of well distances to carcass management locations, these data suggest that the assumption for this assessment is reasonable yet conservative.

It the well is assumed to be 100 m directly downgradient from the temporary storage pile or burial trench, and virus particles move toward the well at the average annual ground water flow rate (i.e., 404 m/yr discussed above), the travel time from breakthrough directly beneath the source to the ground water well is 0.247 yr, or 90 d. This estimate is used for all three soil types; the DAF is not specific to a soil types because it is based on a nationwide distribution of soil data.

Estimated Well Water Concentration

Table 3.3 compares estimated FAD virus concentrations (in $TCID_{50}$/L) in leachate and in well water with and without the effects of dilution attenuation and biological decay. As discussed previously, these estimates are provided to show the amount of reduction that can be attributed to these factors individually and together. For the base case, in which 100 carcasses are placed on bare earth 100 m upgradient from a water well, dilution attenuation is estimated to reduce the concentration of FMDv particles in water by about three orders of magnitude (i.e., by a factor of 1675). The DAF that is the basis for this difference was developed by USEPA using nationwide field data and might under or overestimate dilution attenuation at actual sites.

Biological decay is estimated to have a greater effect than dilution attenuation for the base case. The reduction from biological decay ranges from approximately 4 orders of magnitude with

sandy soil to approximately 6 orders of magnitude with clay. These estimates are based on the same FMDv decay rate measured in liquid cow manure by Schijven et al. (2005). Differences in the estimated decay by soil type are caused by different water velocities reported by USDA NRCS (2004) and UN FAO (2006). Slower velocities are associated with longer travel times and thus greater amounts of decay. The decay estimates also include decay in the ground water aquifer, which is calculated with the median ambient ground water velocity in nationwide site data. The flow velocities might over or underestimate values at actual sites. However, decay is calculated for a well 100 m distant, which is a conservative assumption. Biological decay would be greater than estimated if the well is more than 100 m away.

The concentration estimates in Table 3.3 overestimate concentrations at the well because they do not include sorption-desorption processes that retard the movement of the virus particles, leading to further biological decay and attenuation. The Virulo analysis above indicates a very low probability (i.e., approximately 5.0E-06) of less than 99.99% attenuation before virus particles reach the ground water aquifer.

Table 3-3. Estimated Concentrations of Infective FMDv in the Ground Water Pathway for the Base-case

Concentration Estimate Basis	Average Concentration ($TCID_{50}$/L)		
	Sand	Loam	Clay
Leachate at the Storage Pile	8.8E+07		
Well Water with Dilution Only	5.3E+04		
Well Water with Biological Decay Only	1.5E+03	8.4E+02	1.3E+01
Well Water with Dilution and Biological Decay	8.7E-01	5.0E-01	7.8E-03

$TCID_{50}$ = 50 percent tissue-culture infectious-dose

3.2.5 Cattle Exposure Factor Values

Dairy and beef cattle differ in the amount of air they inhale and in the quantity of food, soil, and water ingested.

Inhalation

- **Respiration Rates:** At rest, dairy cattle take 26–50 breaths per minute (Merck 2015), while beef cattle, which typically weigh substantially more, breath more slowly, approximately 10–30 breaths per minute (Ensminger 1992).
- **Tidal Volume**: The tidal volume of air inhaled for each breath is 7.0–8.0 milliliters (mL)/kg body weight (UWM RARC, Normative Data for Cattle, undated).
- **Air inhalation Rate, Dairy cattle**: 40 (breaths/min) * 7 (mL) * 600 (kg) * 60 (min) = 10,080,000 mL/h = 11 m^3/h.
- **Air inhalation Rate, Beef cattle:** 20 (breaths/min) * 8 (mL) * (1,000) kg * 60 min = 9,600,000 mL/h = 9.6 m^3/h.

Incidental Soil Ingestion Rate

HHRAP (USEPA 2005) methods for estimating chemical uptake by livestock include the incidental ingestion of soil by grazing cattle. Based on a review of available literature, USEPA (2005) recommends a default incidental soil ingestion rate of 0.5 kg per day by grazing, non-dairy cattle.

Forage Ingestion Rate

Based on a review of available literature, USEPA (2005) recommended assuming a total daily feed intake for cattle of 12 kg dry weight (DW) per day. In HHRAP methods, the cattle diet includes forage, silage, and grain. This exposure assessment assumes a forage-only diet. Both grain and silage, which is forage that has been stored and fermented, require processing before use as feed. That means that the grain and silage consumed on the day immediately after the deposition event would be uncontaminated with FMD from deposition, having been harvested at an earlier time and likely a different location. Therefore, it is conservative to assume an all-forage diet for the exposure assessment.

Water Ingestion Rate

In general, cattle drink more water in the summer than in the winter because they pant to lose excess body heat, which also increases loss of water vapor via the lungs. Dairy cattle drink more water than beef cattle (Agriculture and Agri-Food Canada, undated).

- **Water Ingestion Rate – Dairy cattle**: 95 L/day (summer), 77 L/day (winter).
- **Water Ingestion Rate – Beef cattle:** 86 L/day (summer), 55 L/day (winter).

Because these rates are all within the same order of magnitude, the exposure estimates are expected to be less sensitive to the water ingestion rate than to other parameters included in the uncertainty analysis. Therefore, a single ingestion rate assumption, 95 L per day, is used for the assessment.

Summary of Exposure Factor Values

Exposure factor values for dairy and beef cattle are listed below in Table 3.4. Bold text indicates the exposure factor values used for the results presented in Section 4.

Table 3-4. Summary of Exposure Factor Values for Cattle[a]

Exposure Factor	Parameter Symbol	Dairy Cattle	Beef Cattle
Respiration rate (breaths/min)	*Resp*	26–50 (use 40)	10–30 (use 20)
Tidal volume (mL/breath/kg body weight)	*TV*	7	8
Inhalation rate (m^3/h per animal)	*Inh*	**11**	9.6
Soil ingestion rate (kg/day)	*Qs*	**0.5**	
Forage ingestion rate (kg dry forage/kg fresh body weight)	*Qp*	**12**	
Summer water ingestion rate (L/day)	*SWir*	**95**	86
Winter water ingestion rate (L/day)	*WWir*	77	55

Abbreviations and acronyms: min = minute; mL = milliliters

[a] Exposure factors shown in bold are used in the exposure assessment.

3.2.6 Exposure Estimation

In Section 4, exposure estimates are presented separately for inhalation, ingestion of forage and soil, and water ingestion. All exposures are evaluated in units of total $TCID_{50}$ during the exposure event. For the storage pile, the exposure event for all pathways is 48 hours in duration. For carcass burial, exposures from inhalation and ingestion of forage and soil are assumed to be negligible because burial beneath soil prevent suspension of virus particles into air. Water ingestion exposures from burial theoretically could occur over a period of weeks or months, however exposures would decline to negligible levels very quickly due to the combined effects of reduced pH in the carcasses, biological decay of FMDv with time, and attenuation of virus in daily leachate as the source is depleted.

Inhalation

The total $TCID_{50}$ inhaled by one animal during the period is calculated by multiplying the hourly inhalation rate (Table 3.4) by the number of hours of exposure and the 48-hour average air concentration during exposure (Equation 3.5). The exposure duration (*ED*) equals the period over which the air concentration is averaged. Exposures are estimated for each distance from the source using the highest 48-hour average concentrations (i.e., in any direction or 48-hour period).

$$Einh = Inh * ED * Ca \qquad \textbf{(Eqn. 3.5)}$$

where:

Einh = Event total inhalation of viable FMDv, $TCID_{50}$

Inh = Inhalation rate, m^3/h

ED = Exposure duration, 48 hour/event

Ca = 48-hour average concentration of viable virus in air, $TCID_{50}/m^3$

Forage and Soil Ingestion

Equation 3.6 shows how estimates of viable FMDv in soil (Section 3.2.2) and forage (Section 3.2.3) are used to calculate the total FMDv ingested daily by cattle after the 48-hour deposition event. This equation is adapted from HHRAP (USEPA 2005).

$$Eingps = (Qp * Cp) + (Qs * Cs) \quad \textbf{(Eqn. 3.6)}$$

where:

Eingps = Event total ingestion of viable FMDv, $TCID_{50}$

Qp = Quantity of forage eaten by a cow per day, kg DW/d (dry weight per day)

Qs = Quantity of soil eaten by a cow each day, kg DW/d

Cp = Concentration of virus deposited on forage plants, $TCID_{50}$/kg DW

Cs = Concentration of virus deposited on surface soil, $TCID_{50}$/kg DW

In Equation 3.6, the estimated $TCID_{50}$ concentrations in soil (*Cs*) and forage (*Cp*) are multiplied by daily ingestion rates (*Qs* and *Qp*, respectively). Although deposition ends after 48 hours, the deposited virus particles remain available for ingestion in the days and weeks afterward. However, the amount of deposited virus available for ingestion decreases each day due to biological decay. For a series of days, the biological decay rate (1.4E-06 per second) converted to a daily rate is applied with an equation similar to Equation 3.1, to calculate the amount ingested each day. By day 21, biological decay diminishes the daily incremental exposure to 1%, meaning that longer durations have little effect on the total ingestion. Therefore, cattle are assumed to graze for 21 days in an area that receives the maximum deposition estimated by AERMOD. Total ingestion is the sum of the first 21 daily ingestion quantities. In this approach, the amount of virus available for ingestion each day is not affected by grazing in the area on prior days.

Water Ingestion

The total viable FMDv ingested in drinking water during the 2-day exposure is shown in Equation 3.7.

$$Eingw = Ingw * ED * Cw \quad \textbf{(Eqn. 3.7)}$$

where:

Eingw = Event total ingestion of viable FMDv, $TCID_{50}$

Ingw = Water ingestion rate, L/day

ED	=	Exposure duration, 2 days/event
Cw	=	Concentration of viable virus in water supplied to cattle, $TCID_{50}$/L

As explained in Section 3.2.4, the concentration of viable virus in water, *Cw*, is less than the initial concentration of virus in leachate due to dilution and biological decay of virus between the storage pile and water well. However, the calculations to estimate concentrations of infective FMDv in well water do not include sorption-desorption processes that would decrease the concentrations further. Thus, the estimated concentrations overestimate exposure.

3.3 Vectorborne Transmission

No measured data attributing FMD infection from cattle carcasses via vector-borne transmission have been identified, and no methods were identified to estimate transmission, including mechanical transmission, via living vectors to susceptible livestock. Thus, the potential for transmission where vectors could come in direct contact with carcasses is assessed qualitatively based on information on the vectors' ability to carry and/or to transmit the disease to susceptible species at distances of up to 10 km. Insects, birds, and other land animal vectors are discussed and evaluated separately below.

Insects, birds, and/or scavenging animals could become vectors by contacting the carcasses during handling, going on or in the storage pile, materials released from the storage pile (e.g., leachate), or burrowing into the compost windrow or burial trench. However, by the time carcasses are place in a burial trench or compost windrow, they have passed through *rigor mortis* and viable FMDv would remain only on carcass surfaces and in some deep tissue compartments.

When carcasses are in the storage pile, scavenging animals, birds, and insects might contact infected carcasses. During handling, only insects might contact infected carcasses, because handling carcasses involves human actions, which would deter scavenging wildlife from attempting to reach the carcasses. The storage pile is covered with tarp(s) when humans are not present; however, the tarp must be strong and anchored to the ground to be secure from the larger, stronger scavenging mammals (e.g., feral swine) and birds (e.g., ravens, vultures).

Scavenging animals can carry virus particles either externally or internally (e.g., if they fed on carcasses). Externally, infectious FMDv particles could adhere to wildlife surfaces (e.g., cuticle, scales, feathers, and fur) at the infected farm and travel with the wildlife to neighboring farms, where virus particles might drop off and become available to other susceptible species (Cottral 1969). Various species of birds, insects, and scavenging carnivorous mammals, such as coyotes and wolves, in which FMDv does not survive internally, are considered to be potential fomites that may contact off-farm livestock (Cottral 1969).

Some species of insects and mammals are natural hosts of FMDv, and can carry viable internal FMDv, which can also replicate (USDA/APHIS 1994). Deer, moose, and bison are cloven-hooved, obligate herbivore, ruminant ungulates, which like sheep, goats, and cattle, are susceptible to falling ill if infected with FMDv (USDA/APHIS 1994). Swine, both domestic and wild, are also cloven-hooved ungulates which are natural hosts susceptible to FMD, although they are not ruminants; instead they eat almost anything including animal matter. Some other mammals, including rats and gray squirrels, also are hosts of viable FMDv; although they generally do not develop illness (USDA/APHIS 1994). Insects categorized as natural hosts

include house and biting flies (USDA/APHIS 1994). A few other invertebrates, including earthworms and ticks, also are natural hosts (USDA/APHIS 1994).

Natural hosts can be categorized by "carrier length," which is defined as the maximum reported duration of carrier status (i.e., carrying viable, replicating virus but free from illness) or viral shedding (USDA/APHIS 1994). Carrier length probably varies among host species, but few data are available. At least one white-tailed deer remained a carrier of viable FMDv for 11 weeks after infection (Arambulo and Steele 1977; USDA/APHIS 1994) and a 9-month carrier length has been reported for sheep (USDA/APHIS 1994). FMDv has been carried on flies for up to 10 weeks and on ticks for 15 to 20 weeks, but the viability of those FMDv particles was not reported (USDA/APHIS 1994).

The distances travelled by both natural hosts and mechanical vectors determines how far beyond the site of the FMD outbreak those animals might carry the virus. Based on their home range and activity patterns, deer and foxes might travel 10 km or more from the outbreak site (Ahlstrom 1983; Kramer 2015). However, not all natural hosts and/or mechanical carriers are capable of traveling long distances. Rats typically travel only 30 m (100 ft) to 91 m (300 ft) from their nest in search of food (County of Los Angeles, undated). In studies of house flies, 60–80% of marked flies were captured within 1.6 km (1 mile) of their release point, while a smaller percentage of flies were caught 3.2 km (2 miles) from the release site within the first 4 days after they were released (Townsend 1997). Thus, it is unlikely that the typical housefly could travel to farms located 10 km beyond the site of the outbreak. Ticks do not fly; they jump, and their horizontal movement is limited to a few centimeters (University of Rhode Island 2016). However, once on the skin of a mobile animal, bird or mammal, they could be transported beyond 10 km from a carcass management location. At a new location, the ticks might drop off, molt, and reattach to a different animal. The molt, however, would leave external FMDv particles on the ground.

For scavenging wildlife that are not natural hosts to spread FMDv, they would need to pull parts of carcasses from the field, for example prior to collection for the temporary storage pile or from the storage pile. In the field, workers should collect carcasses as they are culled, preventing access for scavenging wildlife. Once carcasses are placed in the temporary storage pile, there would be human activity in the vicinity whenever the tarp over the pile was opened (e.g., for adding or removing carcasses), which would deter daylight scavengers (e.g., crows, ravens, vultures). At night, when there might be no workers present, the tarp, presumably secured to the ground, would prevent ready access by nocturnal scavengers (e.g., foxes).

If appropriate livestock-raising hygienic measures are used (i.e., relatively clean conditions; rat control), the on-site temporary storage pile should not be within the normal foraging range of mammalian scavengers, including rats. If workers discovered disturbances to the covered storage pile in the morning, presumably they would find ways to re-secure the carcass protection and establish scavenger control measures (e.g., on- and off-premises bait and capture stations). Even if one or a few mammalian scavengers such as foxes and coyotes removed parts of carcasses and carried them off the infected premises, they would likely cache (hide) the parts not eaten near dens or feed the part to pups in dens, which are unlikely to be located in livestock pastures.

In areas with active wolf packs, which could conceivably tear open a tarp, remove substantial quantities of carcasses in a single night, and carry them far distances, additional biosecurity measures might be needed for a temporary storage pile. Similarly, in areas with feral swine, tarps

would need to be of strong materials and well secured to the ground (e.g., staked at close intervals).

FMDv can remain infective in bird feathers for 91 hours and in bird droppings for 26 hours (Bullough 1942; Svidorov et al. 1974; Canadian Food Inspection Agency 2013), allowing adequate time for birds to travel far from the site of the outbreak. However, birds must be heavily contaminated with FMDv particles to transmit the disease as mechanical vectors (Wilson and Matheson 1952; Canadian Food Inspection Agency 2013). Data reported by Dillon (2011) indicate that the skin of an infected animal (e.g., cow) is a significant virus reservoir (see Section 3.1.1), and birds such as ravens and crows might come in direct contact with the skin of infected carcasses during the day; however, they would not generally have sufficient time undisturbed during the day to penetrate a tarp.

After considering information on the identity, host status, and transmission potential of insects and wildlife scavengers, the following qualitative conclusions can be drawn about vector transmission associated with the management options and activities:

- **Handling:** Insect vectors might contact carcasses during handling. Given their short-range flights, however, mechanical transmission by flies beyond 10 km is unlikely. If all susceptible livestock within the 10 km response area are not culled, insects pose a greater threat of spreading the FMD outbreak.
- **Temporary Storage Pile:** Although the temporary carcass storage pile is assumed to be covered with a tarp, some scavengers might smell the carcasses and attempt to dig through the tarp when people are not around (e.g., at night for mammals). The tarp is moved for short periods of time as additional carcasses are added to the pile. During this time, insects might contact the carcasses; however, few individual insects are likely to travel 10 km or more to nearby farms with susceptible animals. Scavenging birds and mammals might penetrate a protective tarp when people are not around (e.g., at night) at the temporary storage pile. Wildlife scavengers could carry and transmit FMDv farther than insects. In areas with feral swine or wolves, additional protection could be required, such as temporarily storing the carcasses in lined, leak-resistant roll-offs with secure tarps across the top. Tarp integrity is key to preventing large masses of insects and any kind of scavenging wildlife from contact with the carcasses; monitoring might be required, particularly if not all livestock have been culled within the 10 km response area. The closer susceptible livestock are to a temporary storage pile, the higher the risk that a vector that made contact with infected carcasses could make contact with other susceptible livestock. The number of vector species/types capable of making contact with other susceptible livestock increases with decreasing distances between the storage pile and susceptible livestock.
- **Burial:** The bulk of viable FMDv in carcasses has been inactivated by low pH prior to burial, unless carcasses are placed in the burial trench immediately after euthanasia. In either case, viable virus could still be adsorbed to external surfaces of the carcasses. The burial trench might present an opportunity for scavenging wildlife to contact carcasses. However, the 6 feet of dirt covering the burial trench precludes typical scavenging mammals from reaching the carcasses. Most burrowing small mammals only feed on live insects and other invertebrates in the soils. Avian scavengers would not dig in soils; they only consume carrion that is above ground or floating in water. It is unlikely that the denning activities of foxes and other scavenging mammals would occur immediately over a burial trench.

Exposure of susceptible livestock on farms outside the FMD response area, therefore, is unlikely.

- **Composting:** Again, the bulk of viable FMDv in carcasses has been inactivated by low pH during the two days of temporary storage prior to composting, unless carcasses are immediately placed on the compost windrow when culled. In either case, viable virus could still be adsorbed to external surfaces of the carcasses. Avian scavengers are unlikely to smell or see carcasses in compost piles. One of the functions of the bulking agent (i.e., wood chips) over top of the windrow is to retain some chemicals that cause odors that might attract scavenging mammals to the carcasses. USDA/APHIS recommends that the site be fenced to preclude entrance of larger mammalian scavengers (USDA 2005). Depending on the fencing material, it is possible that larger mammals, such as feral swine or wolves could break through the fence and access the windrow. Monitoring of the integrity of the compost pile covering and fencing is required to ensure that larger scavengers do not reach composted carcasses, particularly in the early weeks of composting when a possibly significant proportion of virus in and on livestock carcasses is still viable.

Overall, the likelihood of mechanical transmission of FMDv via insects and scavengers is low for carcass handling and burial, and somewhat higher for the temporary carcass storage pile and for composting. For the latter two cases, monitoring the integrity of protective measures (i.e., tarp, windrow covering, fence) is important to minimizing the chance of off-site transmission of FMD.

4. Results and Discussion

In presenting the exposure assessment results, this section evaluates whether managing FMD-infected carcass at the outbreak farm site might infect healthy cattle in the surrounding area. Section 4.1 discusses and compares the relative potential for exposures among all of the management options (on-site open burning, air-curtain burning, unlined burial, and composting; off-site fixed-facility incineration, lined landfill, and rendering), including those not quantitatively assessed. Section 4.2 presents the quantitative exposure assessment using "base-case" data and assumptions, which most closely resembles the case evaluated for natural disasters. The base case uses a set of reasonably conservative values based on a review of available literature and previously developed default assumptions for the hypothetical farm site.

The results presented in Section 4.2 are uncertain owing to several gaps in the available scientific data on FMDv. In addition, natural variation in important environmental characteristics from one location to another precludes use of a single scenario to represent possible future events. Important variables that cannot be predicted prior to an event include the scale of mortality, the type of soil, distance to nearest uninfected livestock herd, depth to ground water, and distance of nearest ground water wells that might be used to water livestock. To examine how potential exposures are affected by such factors, Section 4.3 presents an uncertainty analysis where the base-case assumptions are systematically varied.

4.1 Qualitative Exposure Assessment

For reasons discussed in Section 2, exposures are not quantitatively assessed for the three off-site management options and two of the on-site management options. Those options, along with burial and composting, can be qualitatively evaluated based on the degree of thermal destruction and containment provided by the carcass management options.

At high temperatures, if performed in accordance with permit requirements and best practices, burning and incineration options are expected to effectively inactivate the FMDv. If open pyre burning is not performed correctly, some external viable virus particles might rise with warm air plumes as fires start and travel downwind to a neighboring farm. Thus, air-curtain burning, which recirculates most fly ash several times resulting in more complete combustion, is less likely than open-pyre burning to accidentally release viable virus particles to air.

For composting, a large proportion of viable FMDv that remains in carcasses after passing through *rigor mortis* is likely to be inactivated at temperatures typical of carcass compost piles. In general, temperatures of at least 55°C (131°F) must be reached for three or more days to inactivate microbial populations (NABCC 2004). Guan et al. (2010) reported that FMD was inactivated in specimens in compost by day 10 and the viral RNA was degraded in skin and internal organ tissues by day 21. Compost windrow temperatures had reached 50°C and 70°C by days 10 and 19, respectively. However, Schwarz and Bonhotal (2015) reported that FMDv survived considerably longer at lower temperatures in laboratory conditions: as long as 21 days at 30°C and 93 hours at 40°C. Schwarz and Bonhotal (2015) also found that FMDv was inactivated in less than one hour at 50°C in their laboratory compared with survival over 34 to 44.5 hours outdoors in sewage sludge, even though the highest temperature was 48°C. They concluded that survival time depends on physicochemical factors in addition to temperature. Not all parts of a compost row necessarily reach and maintain the temperatures expected to render FMDv inviable in some tissue reservoirs (e.g., bone marrow). Moreover, USDA cautions that the

composting site should be kept isolated from susceptible animals until such time that laboratory testing is unable to recover virus and/or sentinel animals have confirmed that finding.

Temperatures reached during rendering processes also are likely to inactivate the virus. The five management options that include thermal destruction, ranked in order of decreasing temperatures are: off-site incineration, air-curtain burning, open burning, rendering, and composting.

Containment refers to prevention or reduction (e.g., with physical barriers) of releases to the environment, while control refers to limiting releases to acceptable levels. Among the seven carcass management options, the three off-site options provide more containment and control compared with the four on-site options, because commercial facilities must limit their releases to the environment to meet state and federal standards and statutes. The off-site options, therefore, are not ranked relative to each other, although off-site incineration would thoroughly inactivate the virus.

All four of the on-site options include largely unregulated environmental releases. As concluded in the assessment of carcass management options for natural disasters (USEPA 2017), the on-site options can be ranked in order of thermal inactivation of microbes generally: air-curtain burning, open-burning, and composting, with burial offering no high-temperature inactivation. Although these rankings are based on an analysis that included microbes typically found in healthy cattle in the United States, they apply to FMD also. Air-curtain burning recirculates fly ash and gaseous pollutants to result in more complete combustion and higher burn temperatures than open pyre burning and is expected to completely inactivate all virus particles. Open pyres, if not well managed, might result in pockets of uncombusted materials near the edges of the pyre that might travel in wind off-site. Similarly, compost piles require monitoring and management to ensure that internal temperatures sufficient to inactivate FMD are reached throughout a windrow.

The identification of pathways and impacts of pollutants from seven carcass management options are discussed for natural disasters (USEPA 2017). Before any of these seven carcass management options can be used, it may be necessary to handle, move, or temporarily store the carcasses (e.g., while procuring fuels, excavating a burial trench, arranging for biosecure transportation off-site). Based on the discussion of these activities in Section 2.2.1, potential exposures due to handling and temporary storage in a pile on the ground are assessed. Considering biological decay and reduced pH in carcasses upon *rigor mortis*, carcasses in the temporary storage pile contain more viable virus than carcasses during any subsequent phase of management.

4.2 Base Case Exposure Assessment for FMD

The quantitative exposure assessment evaluates the potential for neighboring healthy cattle to be exposed to viable FMDv through two release pathways: to air and to soil, with possible transport to ground water below. This section presents results for the base case, which serves as a baseline of comparison for additional results in Section 4.3. The results for air and soil-to-ground water release pathways are presented in Sections 4.2.1 and 4.2.2, respectively.

The base case exposure estimates presented in this section are compared to $TCID_{50}$ benchmarks identified in Section 2, Table 2.1. The $TCID_{50}$ benchmarks are used as points-of-reference only, and exposure estimates equal to or greater than a benchmark do not necessarily indicate that FMD infection is likely. Likewise, infection may be possible when the exposure estimates are

below the benchmarks. Exposure estimates might be over- or under-estimated for the base case scenario and the base case scenario might over- or under- estimate exposures at actual sites for the following reasons:

- Exposures are determined in part by parameters such as carcass number and weight, soil properties, and meteorology with moderate to high natural variation. Conditions at actual sites might differ from those used in this assessment.
- The exposure assessment includes parameters with high uncertainty due to limitations of available data or methods. Examples of these parameters include the rate FMDv particles are released to air from the carcasses and biological decay rates.
- The exposure assessment uses simplifying assumptions such as details of the carcass management options (duration of temporary carcass storage, pile size and placement, well location) that might differ at actual sites.

The exposure assessment examines how the estimated exposures differ when certain parameters are varied. For releases to air, base case results are presented at distance intervals from the source. The base case results for releases to soil and ground water examine difference by soil type and depth. In Section 4.3, the base case results are used as points-of-reference as factors such as the scale of mortality and biological decay rates are varied. In section 4.3, exposure estimates are compared to the base case and not to $TCID_{50}$ benchmarks.

Because of the uncertainties inherent in the assessment, varying parameter values as described above does not necessarily answer questions such as how far do healthy cattle need to be from the source to be "safe" from infection. However, the results are useful for questions such as:

- How do exposures compare with different soil types?
- Is leaching to ground water affected more by soil type or depth?
- How do exposures change with 10 or 100 times as many carcasses?

In addition, the exposure assessment provides information to help site managers identify potential exposure pathways, to evaluate whether complete pathways are likely to exist given site-specific conditions, and how best to mitigate potential exposures (e.g., storage pile location, liners, tarps).

4.2.1 Air

Cattle can be exposed to FMDv released to air in two ways: (1) inhalation of virus particles in air, and (2) ingestion of virus particles deposited from the air to soil and vegetation. This section estimates exposures separately for inhalation and ingestion.

Inhalation of FMDv Particles in Air

As described in Section 3.2.1, air transport of FMDv emitted from the temporary storage pile is modeled to estimate concentrations in air at distance intervals of 100 m up to1 km and at 1 km intervals extending to 10 km as shown in Figure 4.1. If biosecurity procedures to contain the outbreak are fully implemented, only distances beyond 10 km might include live cattle. Exposure at closer distances is possible if it is infeasible to cull all cattle within the 10-km FMD response area.

Figure 4.1 also shows that virus concentrations in air are highest at 100 m (i.e., closest to the source) and decrease gradually with increasing distance from the source. The figure also shows that there is no strong directional pattern in maximum 1-hour modeled air concentrations.

Table 4.1 shows the estimated inhalation exposure concentrations and total 48-hour exposure estimates by distance from the storage pile. All concentrations are given in units of $TCID_{50}/m^3$. The maximum 48-hour average concentrations identified are presented because this is the duration of storage and exposure. The concentrations at each distance are the highest 48-hour average concentrations in any direction.

Because weather conditions play a large role in air dispersion, AERMOD estimated concentrations for each hour for a full year using hourly meteorological data.[12] The maximum concentrations represent the time periods (e.g., 48 consecutive hours) with the highest average concentrations. Maximum air concentrations and deposition for one 48-hour period over an entire year are similar in all 16 wind directions, which implies that any single 2-day maximum is almost equally likely to occur in any of the 16 directions. Central-tendency (e.g., median, mean) air concentrations and deposition would be higher in the direction corresponding to the prevailing wind direction. The assessment included hours when weather conditions, specifically temperature and relative humidity, would be unfavorable to the survival of the FMDv (i.e., temperatures above 75°F (23.9°C) and a relative humidity less than 55%).

[12] For further information about the meteorological data used for this assessment, see USEPA (2017).

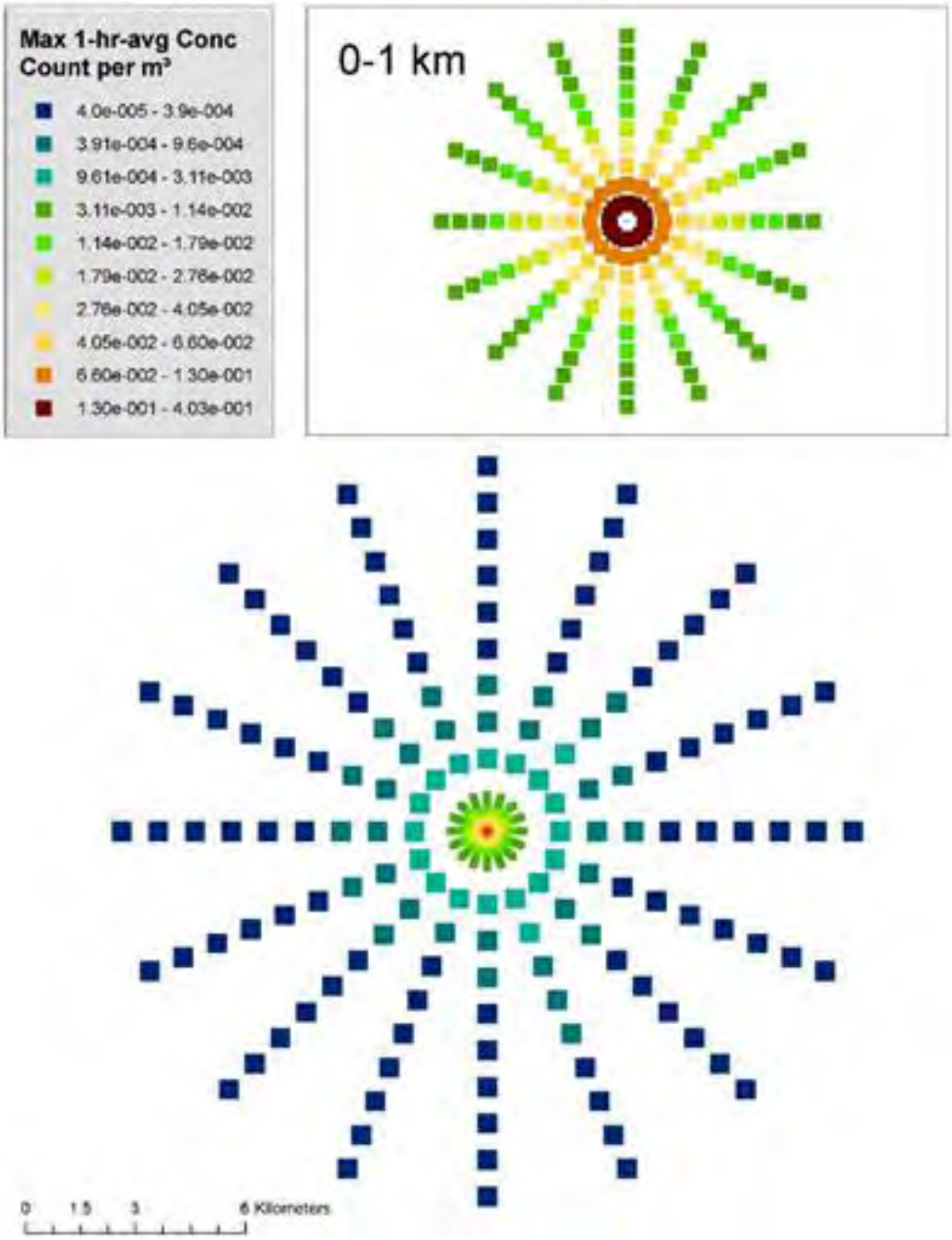

Figure 4-1. AERMOD receptor locations and highest 1-hour FMDv concentrations.

Table 4-1. Base-Case Estimates of Inhalation Exposure for Dairy Cattle

Distance from Source	Highest 48-hour Concentration ($TCID_{50}/m^3$)	Total 48-hour Exposure ($TCID_{50}$)	Exposure Ratio [a]
100 m	9.1E-02	4.8E+01	2.4
200 m	2.7E-02	1.4E+01	0.72
300 m	1.3E-02	6.9E+00	0.352
400 m	8.0E-03	4.2E+00	0.212
500 m	5.4E-03	2.9E+00	0.142
600 m	3.9E-03	2.1E+00	0.10
700 m	2.9E-03	1.5E+00	0.077
800 m	2.3E-03	1.2E+00	0.061
900 m	1.8E-03	9.5E-01	0.0487
1 km	1.5E-03	7.9E-01	0.0400
2 km	4.0E-04	2.1E-01	0.0107
3 km	1.8E-04	9.5E-02	0.0047
4 km	9.7E-05	5.1E-02	0.0026
5 km	5.9E-05	3.1E-02	0.0016
6 km	3.9E-05	2.1E-02	0.0010
8 km	2.7E-05	1.4E-02	7.0E-4
9 km	1.9E-05	1.0E-02	5.0E-4
10 km	1.4E-05	7.4E-03	4.0E-4

Abbreviations and acronyms: $TCID_{50}$ = 50 percent tissue-culture infectious-dose

[a] The Exposure ratio is the estimated 48-hour inhalation exposure divided by the $TCID_{50}$ benchmark (i.e., 20 $TCID_{50}$, see Table 2.1).

The 48-hour total inhalation exposure estimates in Table 4.1 are calculated with Equation 3.5 as described in Section 3.2.6. The exposure estimates are based on the inhalation rate for dairy cattle (11 m^3/hour), which is slightly higher than the inhalation rate for beef cattle (9.6 m^3/hour).

Exposure ratios in Table 4.1 are calculated by dividing the inhalation exposure by the inhalation benchmark of 20 $TCID_{50}$ (see Table 2.1). If the specific inhalation rates for dairy cattle and beef cattle had been used in the calculation, the exposure ratios for dairy and beef cattle 100 m from the storage pile are 2.4 and 2.1, respectively.

Ingestion of Virus Particles on Soil and Vegetation

Along with air concentrations of FMDv particles, air dispersion modeling provided rates of virus particle deposition to the ground. Virus particles deposited to vegetation are grazed by cattle, and soil is incidentally ingested along with vegetation. Methods for estimating concentrations of FMDv in surface soil and on vegetation and are described in Section 3.2.2 and Section 3.2.3, respectively, and the method for estimating ingestion exposure is described in Section 3.2.6.

Table 4.2 presents the total ingestion estimate for the base case in units of $TCID_{50}$ per 48-hour event. Ingestion exposures are presented for the location with the highest exposure concentration

at any of the 304 locations modeled. The highest concentration is 100 m from the source, which is the closest distance evaluated.

Although the exposure assessment is based on some parameters with considerable uncertainty (e.g., data to estimate emission rates at the source), the exposure estimates are likely conservative due to several assumptions used to estimate ingestion. The cattle are assumed to eat a diet entirely of forage (i.e., not supplemented with uncontaminated grain or silage), which they obtain by grazing entirely at the locations with the greatest deposition. In addition, the cattle are assumed to graze immediately following the end of deposition, before further biological decay of the virus can occur.

The results in Table 4.2 include the 48-hour deposition of FMDv, the estimated concentrations of FMDv in soil and forage at the end of deposition, the total ingestion of viable virus over the 21-day exposure duration, and the exposure ratio calculated with the ingestion benchmark, 1E+05 $TCID_{50}$.

Table 4-2. Forage and Soil Ingestion Exposure Results

Total 48 h Deposition, with Decay ($TCID_{50}/m^2$)	FMDv Concentration in Soil After 48 h ($TCID_{50}$/kg)	FMDv Concentration in Forage After 48 h ($TCID_{50}$/kg-dw)	Amount of FMDv Ingested by Cattle Over 21 Days ($TCID_{50}$)	Exposure Ratio for 21-day Exposure
2.8E+02	9.2E+00	2.8E+02	2.7E+04	2.7E-01

Abbreviations and acronyms: dw = dry weight; FMDv = foot and mouth disease virus; $TCID_{50}$ = 50 percent tissue-culture infectious-dose

4.2.2 Ground Water Ingestion

Fluids released from carcasses during the early stages of decomposition, while carcasses are in the temporary storage pile, can seep into the ground, eventually passing through soil to ground water. As discussed in Section 4.1, the fluid released from the temporary storage pile is expected contain more viable virus than releases at later steps of carcass management, in part because a pH decrease during *rigor mortis* is unfavorable to survival of the virus.

Neighboring live cattle could be exposed to FMDv in ground water if their drinking water comes from an affected well. For that situation to occur, the well must be located downgradient (i.e., in the direction of ground water flow) from the source and the aquifer would need to be relatively shallow. In addition, a sufficiently large load of virus must reach the ground water at the well fast enough to still contain viable virus particles. The amount of time required for horizontal transport to the neighboring well depends on the rate of ground water flow and the distance from the source.

As discussed in Section 3.2.4, simulations with the Virulo model indicate that FMDv released from the temporary carcass storage pile will have a very low probability of reaching ground water without at least 99.99% attenuation. The risk that 99.99% attenuation not being met with at least a meter of soil is approximately 5.0E-06. Virulo estimates attenuation based on hydrogeological processes and virus particle sorption-desorption in the soil between the source and the water table. It does not estimate concentrations of virus particles in ground water and does not address biological decay or attenuation processes in the ground water.

To examine the ground water exposure pathway further, a series of calculations were performed to estimate the FMDv concentration in a well 100 m downgradient from the storage pile. These calculations include biological decay and dilution attenuation between the storage pile and the well. These simple calculations overestimate exposure because they do not include the complex vadose zone processes simulated by Virulo,

Table 4.3 presents the estimated concentrations of viable virus in well water, as well as the one-day ingestion exposure per cow, and the exposure ratio (i.e., one-day exposure relative to the ingestion benchmark). Note that a cow provided drinking water from the well for more than one day will have an increased cumulative exposure and risk of infection, and in a herd of cattle provided drinking water from the same well there is an increased risk that at least one will be infected. FMD is highly contagious and is likely to spread through the heard if at least one cow is infected.

Exposure to FMDv from ground water ingestion decreases with greater soil depths between the carcass storage pile and ground water. Because clay is less permeable than silty loam or sand, water and virus particles move more slowly through the vadose zone. With a slower rates of movement in clay than other soils, more biological decay occurs before the virus particles reach ground water. Table 4.3 shows that soil depth has a greater effect on exposure with clay soils than with silty loam or sand.

Table 4-3. Base Case Estimates of Water Ingestion Exposure

Soil Depth (m)	Concentration of Viable FMDv in Ground Water ($TCID_{50}$/L)			One-day Ingestion Exposure per Cow ($TCID_{50}$/day)			Exposure Ratio		
	Sand	Silty Loam	Clay	Sand	Silty Loam	Clay	Sand	Silty Loam	Clay
0.5	9.3E-01	7.0E-01	8.8E-02	8.8E+01	6.7E+01	8.3E+00	8.8E-04	6.7E-04	8.3E-05
1	8.7E-01	5.0E-01	7.8E-03	8.3E+01	4.8E+01	7.4E-01	8.3E-04	4.8E-04	7.4E-06
1.5	8.2E-01	3.6E-01	6.9E-04	7.8E+01	3.4E+01	6.6E-02	7.8E-04	3.4E-04	6.6E-07
2	7.7E-01	2.6E-01	6.2E-05	7.4E+01	2.4E+01	5.9E-03	7.4E-04	2.4E-04	5.9E-08
3	6.9E-01	1.3E-01	4.9E-07	6.5E+01	1.2E+01	4.7E-05	6.5E-04	1.2E-04	4.7E-10
4	6.1E-01	6.7E-02	3.9E-09	5.8E+01	6.4E+00	3.7E-07	5.8E-04	6.4E-05	3.7E-12
5	5.4E-01	3.4E-02	3.1E-11	5.1E+01	3.3E+00	2.9E-09	5.1E-04	3.3E-05	2.9E-14
6	4.8E-01	1.7E-02	2.4E-13	4.5E+01	1.7E+00	2.3E-11	4.5E-04	1.7E-05	2.3E-16

FMDv = Foot and mouth disease virus; $TCID_{50}$ = 50 percent tissue-culture infectious-dose

4.3 Uncertainty Analysis

The findings presented in Sections 4.1 and 4.2 are based on several assumptions for the base case (e.g., the number of carcasses; environmental conditions; configuration, siting, and management of the storage pile). These parameter values are likely to vary substantially across locations and by season, and data by which to estimate releases of FMDv to air and leachate are limited. Although the assessment approach generally uses conservative values for parameters that vary substantially in the real world, parameters for which data are limited and the value selected is highly uncertain (e.g., range and central tendency of values in the real world are unknown), could result in over- or underestimates of exposure.

This section examines the sensitivity of the base case exposure estimates to the most uncertain parameter values. The uncertainty analysis uses the same modeling framework developed for the base case, with the parameters listed below varied one at a time over a range of feasible conditions.

- **Scale of mortality** – Larger numbers of carcasses would release more FMDv to air and the ground.
- **Aerosol release rate** – The aerosol release rate from cattle carcasses to air is based on live animals.
- **Viral load to leachate** – The amount of virus released in leachate over the first 48 hours is unknown.
- **Soil type and depth to soil** – The type of soil and the depth of soil to ground water beneath the storage pile or burial trench affects the potential for exposure via drinking water. These parameters were varied for the base case and are included in the uncertainty analysis as well.
- **Biological decay rate** – Exposure concentrations would be larger if the biological decay rate is slower.

4.3.1 Uncertainty Analysis for Air Exposure Pathways

Table 4.4 shows how selected parameter values are varied for the air exposure pathways. Inputs to AERMOD are varied to examine the sensitivity of exposure to changes in the particle emission rate, the number of carcasses, and the biological decay rate. Except for the parameters listed in Table 4.4, all AERMOD runs are performed with the same data and assumptions as the base case described in Section 4.2.1.

Inhalation of FMDv Particles in Air

Virus particle emission rates are varied from the base-case estimate of 116 $TCID_{50}$ per second up to 1 million $TCID_{50}$ per second. Figure 4.2 shows how this range of values affects the inhalation exposure by distance. In the figure, as well as Figures 4.3 through 4.11, the base-case results are shown as a solid line. All exposure estimates are indexed to the base-case exposure estimate at 100 m from the source. That is, all exposure estimates are divided by the exposure estimated for the base case at 100 m. A red horizontal line distinguishes estimates greater than or less than the index estimate, which has a value of 1. The vertical axis is the level of exposure relative to the base case values, which are provided in Section 4.2.

Figure 4.2 shows that estimated exposures decrease by approximately two orders of magnitude within the first kilometer from the source and about two additional orders of magnitude between 1 and 10 km. With the AERMOD air dispersion modeling framework, the FMDv concentrations

in air are directly proportional to the emission rate at all distances. This is evident because the curves for the varied particle emission rates are equally spaced by order-of-magnitude intervals. For example, a 1,000-fold increase in emissions results in a 1,000-fold increase in exposure at all distances. With a 1,000-fold increase in emissions, exposures are greater than the highest base case exposure (i.e., at 100 m) to a distance of 4 km, and with one additional 10-fold increase exposures are greater than the highest base case estimate at all distances within 10 km.

Table 4-4. Uncertainty Analyses for Air Exposure Pathways[a]

Scenario	Number of Carcasses	Pile Area (m^2)	Particle Emission Rate, Whole Pile ($TCID_{50}$/sec)	Particle Emission Rate per Unit Area ($TCID_{50}/m^2$)	Biological Decay Rate (sec^{-1})
Particle Emission Rate					
Base case	100	96.72	**116**	1.2	1.9E-4
Rounded base case [b]	100	96.72	**100**	1	1.9E-4
10 x base case	100	96.72	**1,000**	10	1.9E-4
100 x base case	100	96.72	**10,000**	100	1.9E-4
1,000 x base case	100	96.72	**100,000**	1,000	1.9E-4
10,000 x base case	100	96.72	**1,000,000**	10,000	1.9E-4
Number of Carcasses					
Base case	**100**	96.72	116	1.2	1.9E-4
5 x base case	**500**	483.6	580	1.2	1.9E-4
10 x base case	**1,000**	967.2	1,160	1.2	1.9E-4
50 x base case	**5,000**	4,836	5,800	1.2	1.9E-4
100 x base case	**10,000**	9,672	11,600	1.2	1.9E-4
Biological Decay Rate					
Base scenario	100	96.72	116	1.2	**1.9E-4**
10 x base case	100	96.72	116	1.2	**1.0E-3**
Rounded base case	100	96.72	116	1.2	**1.0E-4**
1/10 x base case	100	96.72	116	1.2	**1.0E-5**
1/100 x base case	100	96.72	116	1.2	**1.0E-6**

$TCID_{50}$ = 50 percent tissue-culture infectious-dose

[a] Parameter values in bold text are varied. All other parameters are held constant.

[b] Scenario is not modeled because it is close to the base-case value.

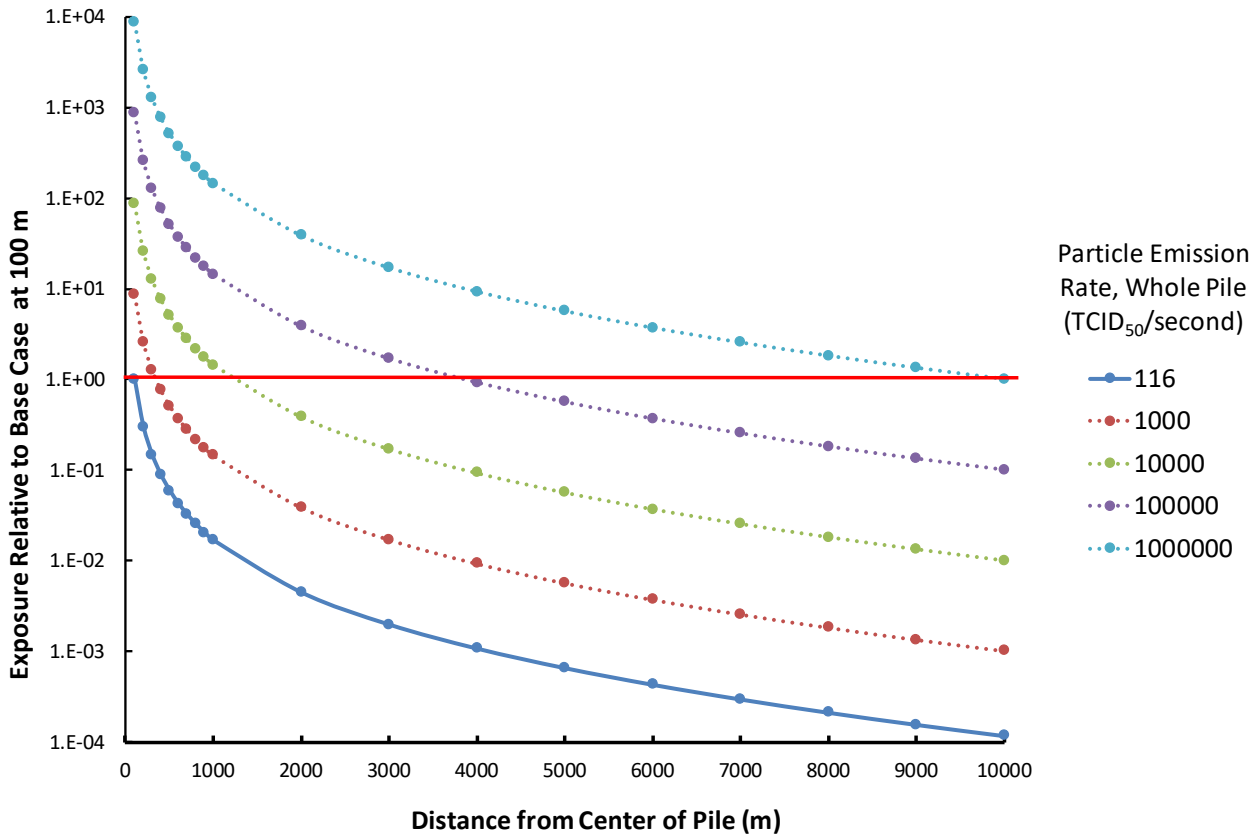

Figure 4-2. Uncertainty analysis for particle emission rates to air, inhalation exposure relative to base case, for dairy cattle with distance from the storage pile.

Figure 4.3 shows how inhalation exposure changes with larger numbers of carcasses. As expected, managing greater numbers of caresses leads to greater levels of exposures. The amount of increase is approximately proportional to the number of carcasses beyond the first few hundred meters from the source. At locations close to the storage pile, exposure estimates are affected by the size and configuration of the pile. Because distance is measured from the center of the pile, the distance from the nearest edge is not necessarily the same with different configurations. These differences affect the concentration unequally, particularly at distances close to the sources.

Air concentrations of FMDv, and exposures, drop off steeply with distance. For example, with 100 times as many carcasses (i.e., 10,000 carcasses), exposure is no greater than the highest baseline exposure (i.e., at 100 m) at distances beyond about 1200 m.

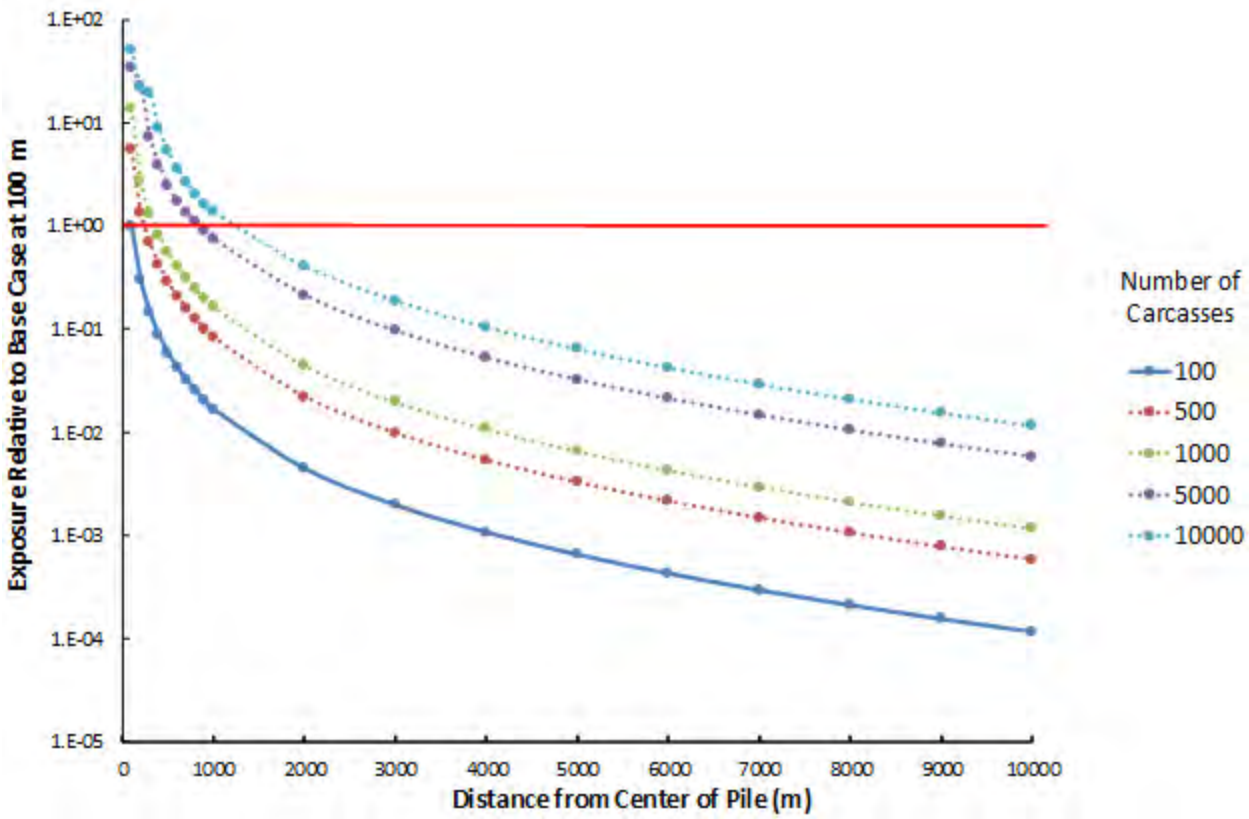

Figure 4-3. Uncertainty analysis for the number of carcasses, inhalation exposure for dairy cattle relative to the base case, with distance from the storage pile.

Inhalation of viable FMDv by neighboring live cattle is insensitive to a varying the virus decay rate over five orders of magnitude. As shown in Figure 4.4, inhalation exposures are similar to the base case within approximately the first kilometer for the selected biological decay rates. Because more time for decay elapses before virus particles reach farther distances, differences in the decay rate have an increasing effect on exposure with distance. However, exposure estimates remain fairly insensitive to the decay rate at 10 km where a 1,000-fold difference in the decay rate results in a less than a 50-fold change in exposure.

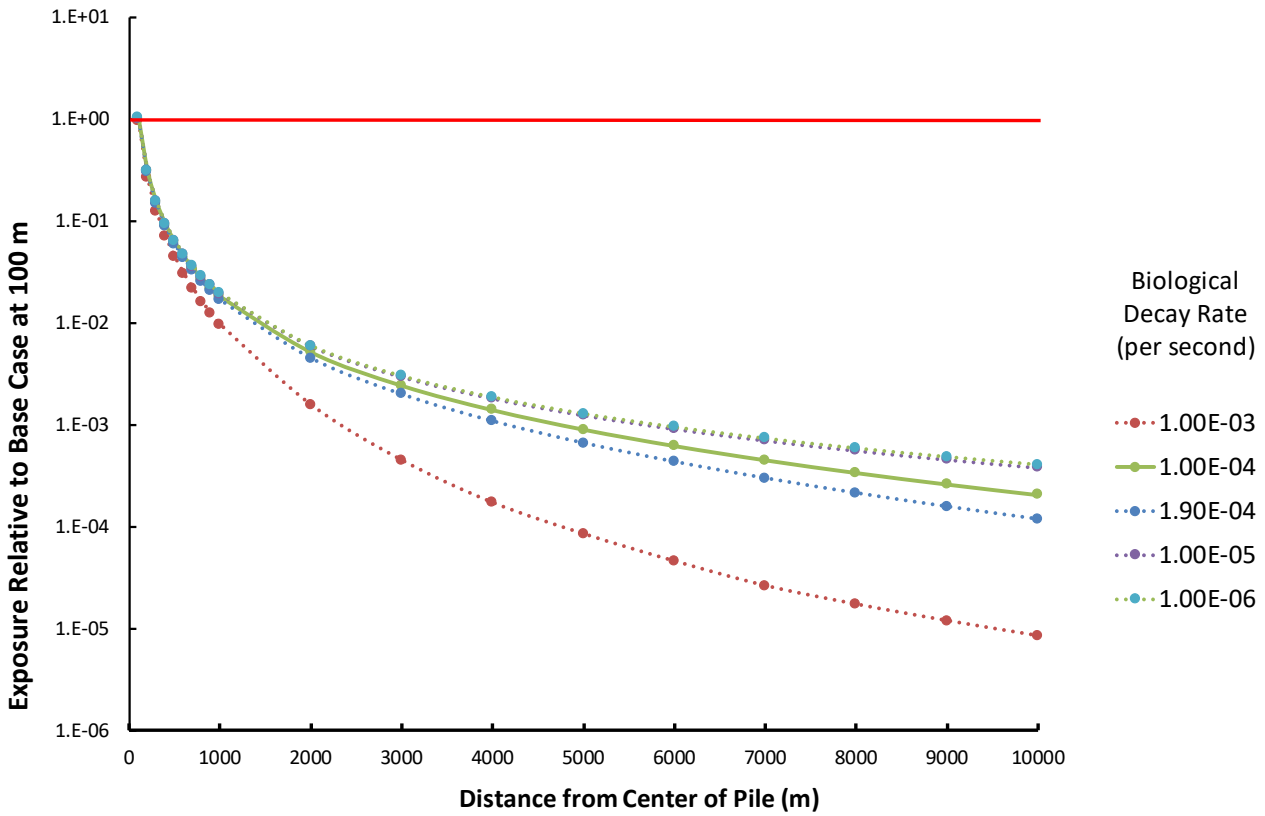

Figure 4-4. Uncertainty analysis for the biological decay rate, inhalation exposure for dairy cattle relative to the base case, by distance from the storage pile.

Ingestion of Virus Particles on Soil and Vegetation

Figures 4.5 through 4.7 show how varying parameter values affect ingestion by neighboring cattle of FMDv particles that settled from the air to forage vegetation and soil. These figures include results only for the location with the highest total deposition, which is at 100 m from the storage pile. As described in Sections 3.2.2 and 3.2.3, ingestion exposure by grazing cattle is estimated as the total $TCID_{50}$ ingested over the first 21 days after the 48-hour release. The base case exposure estimate, 2.7E+04 $TCID_{50}$, is included in Table 4.2. Relative to this baseline, increasing the virus particle emission rate used in the assessment results in proportional increases in exposure. This finding is seen in Figure 4.5 and is consistent with the related results for inhalation exposure shown in Figure 4.2.

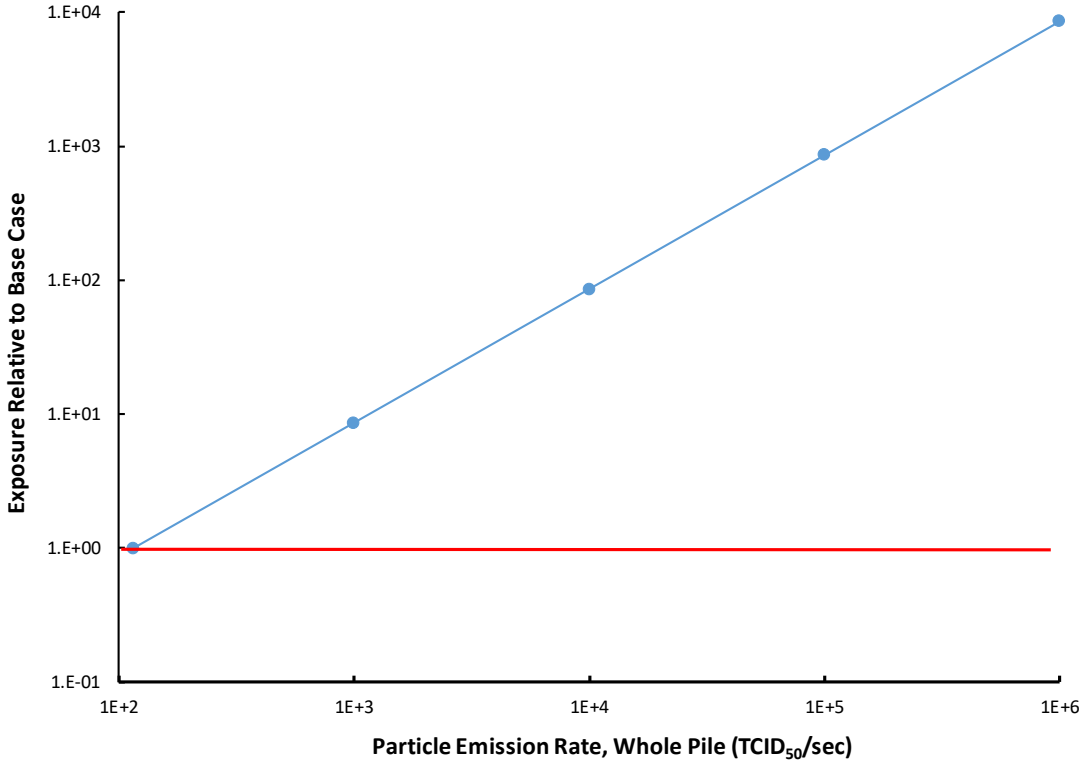

Figure 4-5. Uncertainty analysis for particle emissions to air, ingestion exposure for dairy cattle relative to the base case at 100 m from the storage pile.

Figure 4.6 shows the uncertainty analysis for the number of carcasses, considering ingestion exposure of neighboring cattle grazing 100 m from the source. Increasing the number of carcasses from 100 to 10,000 (100 times) increases exposure by about 50 times. The same relationship is seen in the inhalation exposures with increasing number of carcasses (Figure 4.3).

Foraging exposure is insensitive to changes in the biological decay rate as seen in Figure 4.7. This finding is consistent with the uncertainty analysis for inhalation exposure (Figure 4.3)

For the exposure pathways (i.e., inhalation and forage ingestion) that begin with FMDv releases to air from the carcass storage pile, the uncertainty analysis shows that exposures are directly proportional to the particle emission rate, which is a parameter of particular uncertainty. Exposures are moderately sensitive to the number of carcasses, and least sensitive to biological decay rates. Results for the inhalation and ingestion pathways show the same relationships to changes in these parameters. This analysis suggests the particle emission rate as a priority for further research.

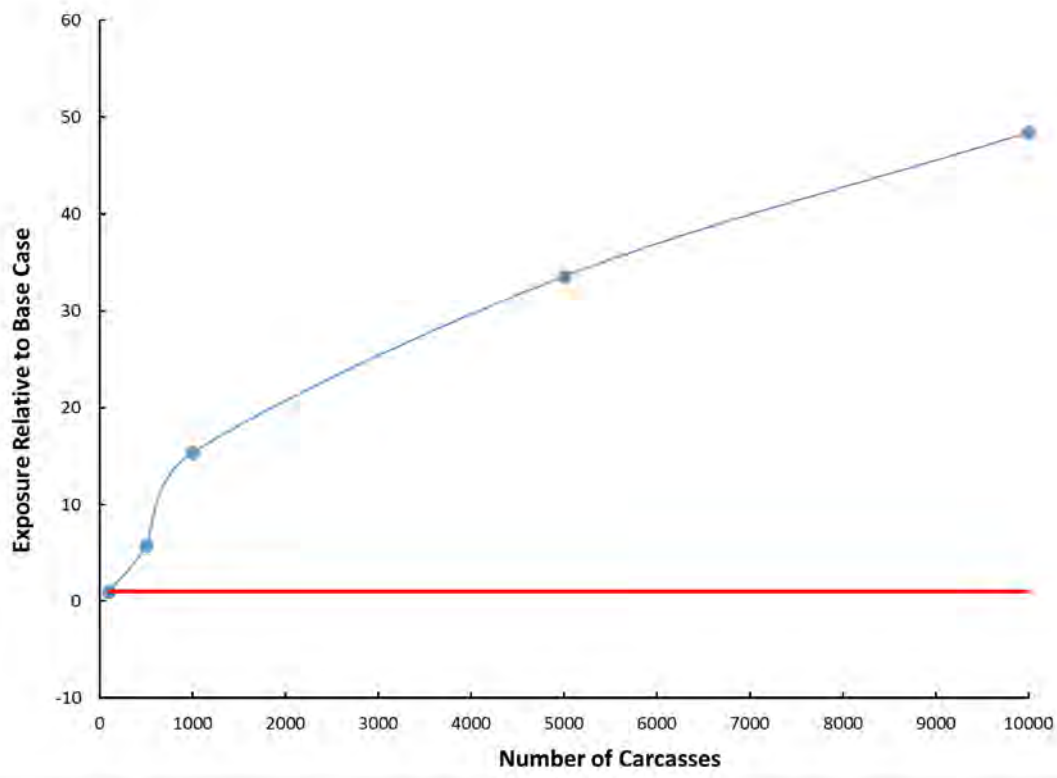

Figure 4-6. Uncertainty analysis for number of carcasses, ingestion exposure for dairy cattle relative to the base case at 100 m from the storage pile.

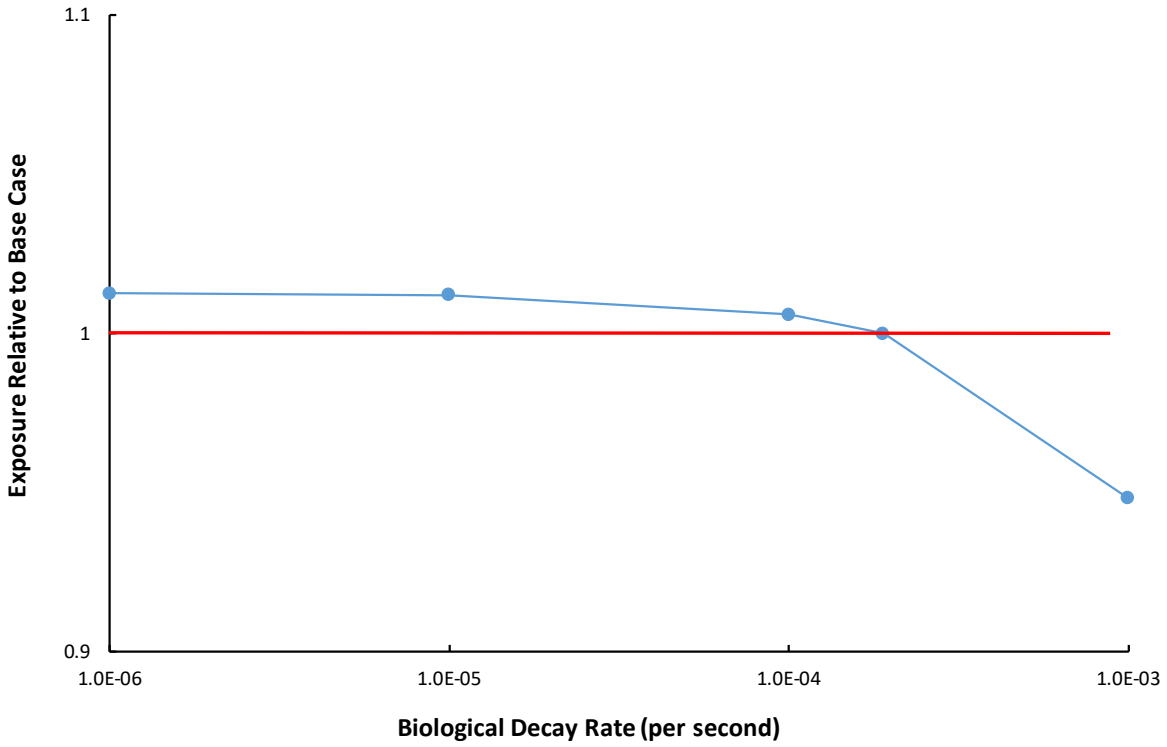

Figure 4-7. Uncertainty analysis for the biological decay rate, ingestion exposure for dairy cattle relative to the base case at 100 m from the storage pile.

4.3.2 Uncertainty Analysis for the Ground Water Exposure Pathway

Table 4.5 shows the uncertainty analysis parameter values for the ground water ingestion pathway. Like the base-case results (Section 4.2.2), the uncertainty analysis includes results for three soil types (sand, silty loam, and clay) and depth to ground water from 0.5 to 6 m.

It is important to note that the results presented in this section evaluate the effects of biological decay and dilution attenuation between the storage pile and a water well 100 m downgradient. These results over-estimate potential exposures because they do not include hydrogeological processes that tend to retard and attenuate virus particles in the vadose zone. The Virulo analysis presented in Section 3.2.4 indicates high likelihood that these processes will achieve at least 99.99% attenuation with at least 1 m of sand, silty-loam, or clay.

As context for results presented in this section, many states recommend or mandate minimum depths of unsaturated soil beneath a carcass burial pit to protect ground water quality. These distances are as little as 1 ft (~0.3 m), but more typically are between 3 ft (~1 m) and 5 ft (~1.5 m) (NABCC 2004). Distance to ground water is not specified for temporary storage piles, but its consideration is relevant to ground water protection.

Particle Release Rate

Figures 4.8 through 4.10 show the sensitivity of water ingestion exposure estimates to virus particle release rates. The three figures correspond to results for sand, silty loam, and clay, respectively. All exposure estimates are indexed to the base case exposure estimate with 1 m of silty loam. The red horizontal line in each figure is the index value of 1. The base case exposure estimates are presented in Section 4.2.2.

The release rates (in $TCID_{50}$/carcass-day) vary over four orders of magnitude with the base-case (dark blue solid line for 9.44+08 $TCID_{50}$/cow) value in the center of the range.

Table 4-5. Uncertainty Analyses for the Ground Water Exposure Pathway for Temporary Storage Pile[a]

Scenario	Number of Carcasses	Pile Area (m^2)	Leachate per Carcass per Day (L/day)	Particle Release Rate, per Carcass (count/day)	Starting Leachate Concentration (count/L)	Biological Decay Rate (s^{-1})
Particles Released per Carcass per Day						
Base case	100	96.72	10.7	**9.4E+8**	8.8E+07	1.4E-6
1/100 x base case	100	96.72	10.7	**1.0E+7**	9.4E+05	1.4E-6
1/10 x base case	100	96.72	10.7	**1.0E+8**	9.4E+06	1.4E-6
Rounded base case	100	96.72	10.7	**1.0E+9**	9.4E+07	1.4E-6
10 x base case	100	96.72	10.7	**1.0E+10**	9.4E+08	1.4E-6
100 x base case	100	96.72	10.7	**1.0E+11**	9.4E+09	1.4E-6
Number of Carcasses						
Base case	**100**	96.72	10.7	9.4E+8	8.8E+7	1.4E-6
1/10 x base case	**10**	9.7	10.7	9.4E+8	8.8E+7	1.4E-6
5 x base case	**500**	483.6	10.7	9.4E+8	8.8E+7	1.4E-6
10 x base case	**1,000**	967.2	10.7	9.4E+8	8.8E+7	1.4E-6
50 x base case	**5,000**	4,836	10.7	9.4E+8	8.8E+7	1.4E-6
100 x base case	**10,000**	9,672	10.7	9.4E+8	8.8E+7	1.4E-6
Biological Decay Rate						
Base case	100	96.72	10.7	9.4E+8	8.8E+07	**1.4E-6**
10 x base case	100	96.72	10.7	9.4E+8	8.8E+07	**1.0E-05**
Rounded base case	100	96.72	10.7	9.4E+8	8.8E+07	**1.0E-06**
1/10 x base case	100	96.72	10.7	9.4E+8	8.8E+07	**1.0E-07**
1/100 x base case	100	96.72	10.7	9.4E+8	8.8E+07	**1.0E-08**

[a] Parameter values in bold text are varied. All other parameters are held constant.

Notes:

- Assumes 75 L leaches from a 454 kg animal in the first week (i.e., Young et al. (2001) stated 33% released in first 2 months with 16.5% in first week). Assuming an exponential decrease in leachate release (e.g., half as much released one day to the next), one would expect 38 L on day 1 and 19 L on day for a total of 57 L (or 28.5 L/day).
- The maximum amount leached assumes the full 16.5% expected over the first week leaches during the first two days alone, or 75 L (divided by 2 = 38 L/day).

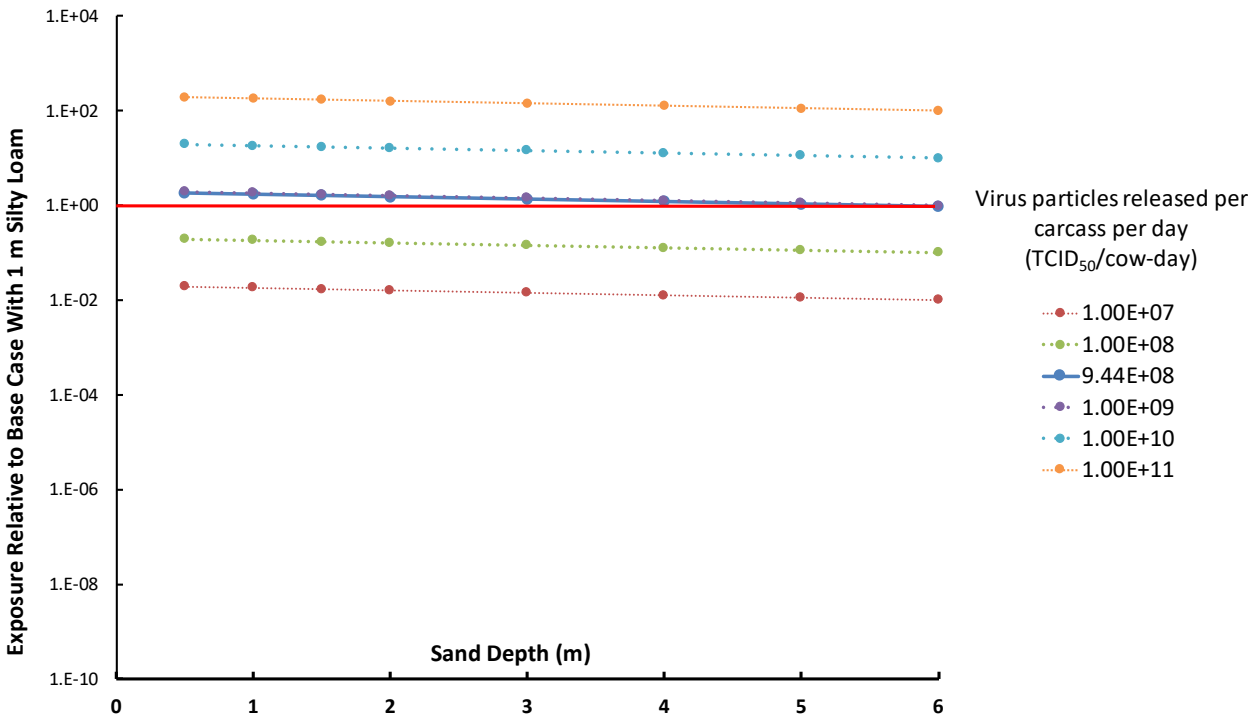

Figure 4-8. Uncertainty analysis for the particle release rate, water ingestion exposure for dairy cattle by depth of sand, relative to base case exposure with 1 m silty loam.

Comparing the slopes of the lines in the three figures shows that sand allows higher permeation and transport of virus particles than the finer soil types, silty loam (Figure 4.9) and clay (Figure 4.10). For the range of particle release rates included in the uncertainty analysis, increasing the depth of sand between the storage pile and the water table provides little additional protection from exposure. Estimated exposures decline rapidly with additional depth of clay soil. For all soil depths and types the exposure estimates are proportional to the particle release rate

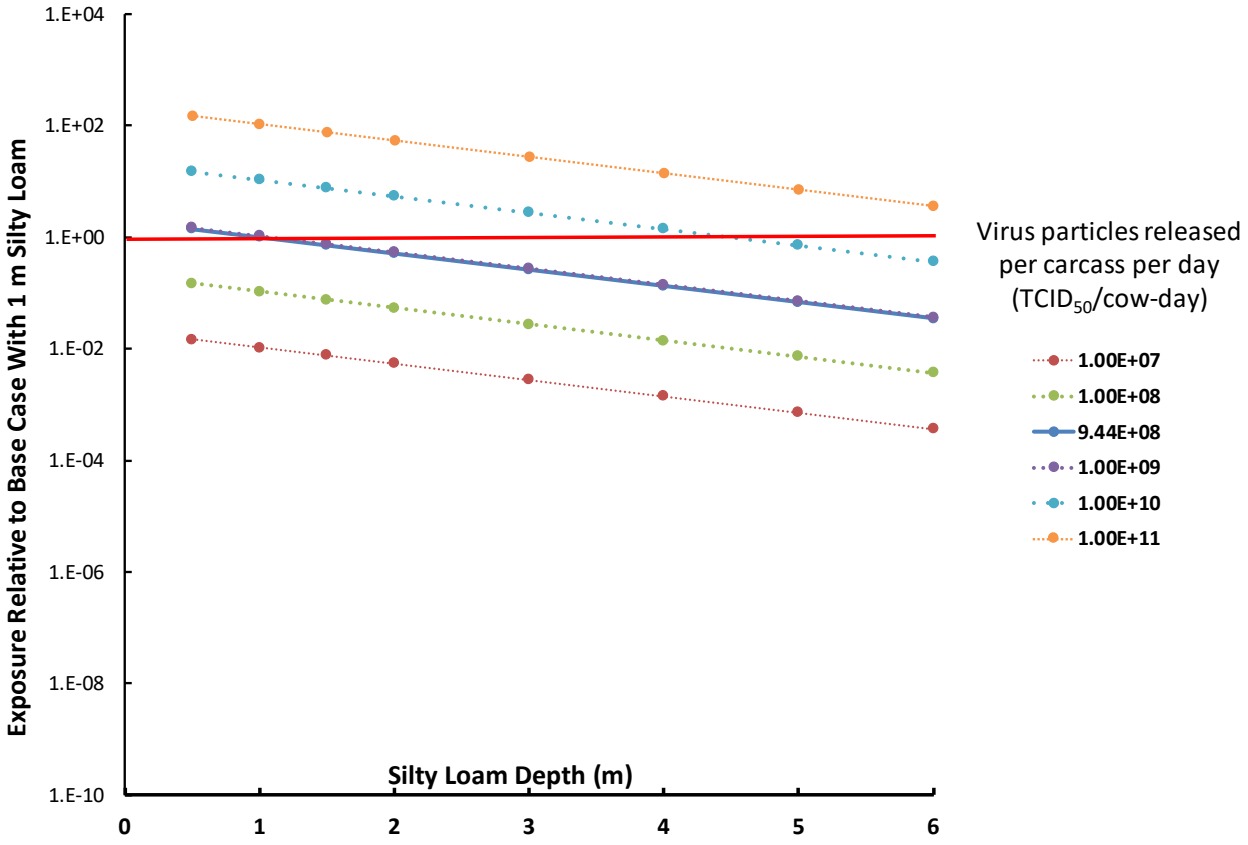

Figure 4-9. Uncertainty Analysis for the Particle Release Rate, Water Ingestion Exposure for Dairy Cattle by Depth of Silty Loam, Relative to Base Case Exposure with 1 m Depth.

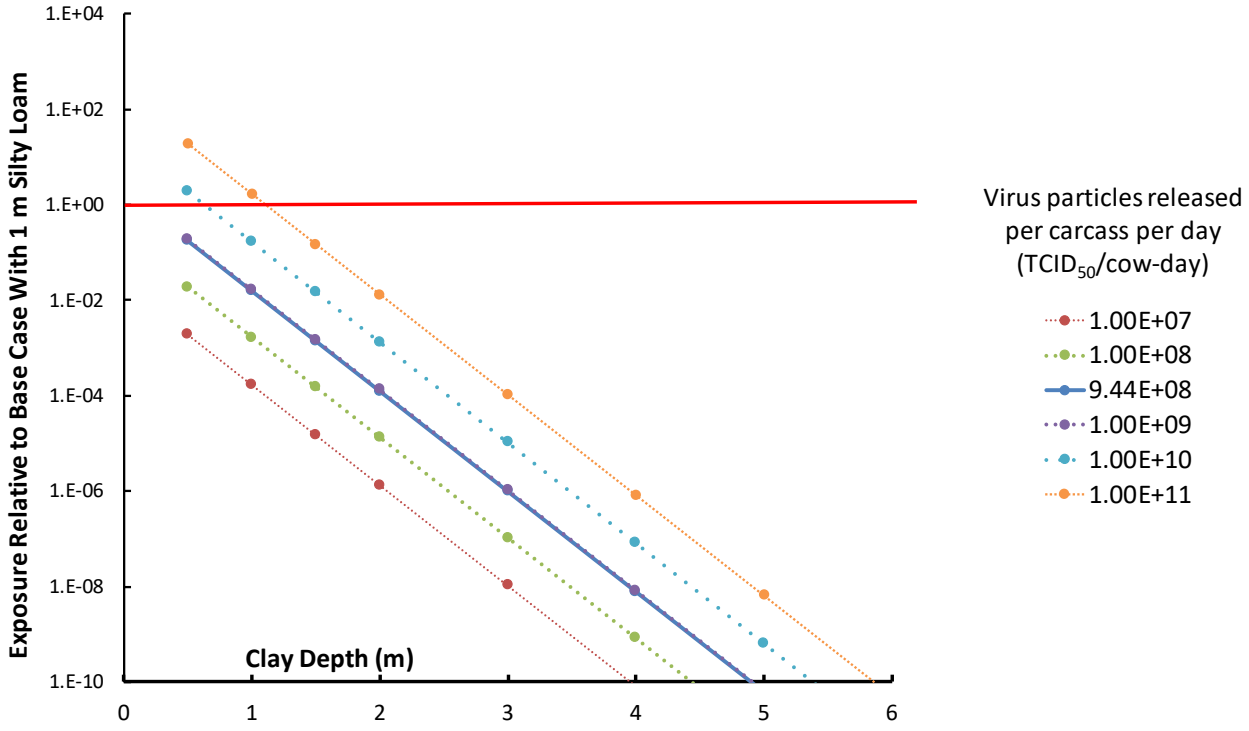

Figure 4-10. Uncertainty analysis for the particle release rate, water ingestion exposure for dairy cattle by depth of clay, relative to base case exposure with 1 m silty loam.

Number of Carcasses

With more carcasses, the amount of leachate released from the storage pile increases. The amount of leachate seeping into the ground per unit area (e.g., per m^2) will remain the same as long as long as the pile size grows horizontally proportional to the number of carcasses. With no change in the amount of leachate per area or in the concentration of infective FMDv in the leachate, physical, chemical, and biological processes in the soil will result in the same concentrations of infective virus in leachate when it reaches ground water. When developing DAFs, as described in Section 3.2.4, USEPA (1996) performed sensitivity analyses for parameters included it its Monte Carlo modeling approach. USEPA identified that the area of the leachate source (e.g., landfills) as having a large effect on dilution attenuation. Based on this finding, USEPA provided DAFs for a range of source areas, and that information is used to identify the DAFs in Table 4.6. Larger DAF values result in greater dilution between the source and the downgradient water well.

Table 4-6. Dilution Attenuation Factors by Area of Storage Pile and Number of Carcasses

Number of Carcasses	Area of Storage Pile (m^2)	DAF
10	9.7	13929
100	96.7	1675
500	483.6	381
1,000	967.2	201
5,000	4836	46
10,000	9672	24

DAF = dilution attenuation factors

Figure 4.11 shows the relationships between the number of carcasses, soil type, and the estimated water ingestion exposure. Exposure estimates are indexed to the base case (i.e., 100 carcasses) value with 1 m of silty loam. For all soil types, greater numbers of carcasses cause greater exposures. However, the rate of increase in exposure declines when the number of carcasses is greater than 1,000. The relationship between number of carcasses and estimated exposure results from the DAFs, which are based on USEPA's (1996) Monte Carlo analysis using databases of landfill site data.

Biological Decay

The biological decay rate is a measure of the persistence of infective FMDv in environmental media.[13] The FMDv is more persistent in the leaching to ground water pathway than in the air emission pathways because the viral particles in water are protected from drying. The biological decay rates used in this assessment for FMDv in air and water are 1.9E-04 per second and 1.4E-06 per second, respectively. The bases of these values are discussed in Sections 3.1.1 and 3.1.2.

Figures 4.12 through 4.14 present the uncertainty analysis for the biological decay rate in the drinking water exposure pathway. As seen in the other uncertainty analyses, the potential for exposure through drinking water is greatest when the storage pile is placed over sand and least when placed over clay. With the slowest decay rates (i.e., 1E+04 and 1E+05), the exposure estimates are similar with the three soil types and they are not sensitive to soil depth, presumably because there is a low amount of decay over the estimated time of travel.

[13] Persistence refers to the continued presence of a particular virus type in the environment over a period time (Embrey et al. 2004).

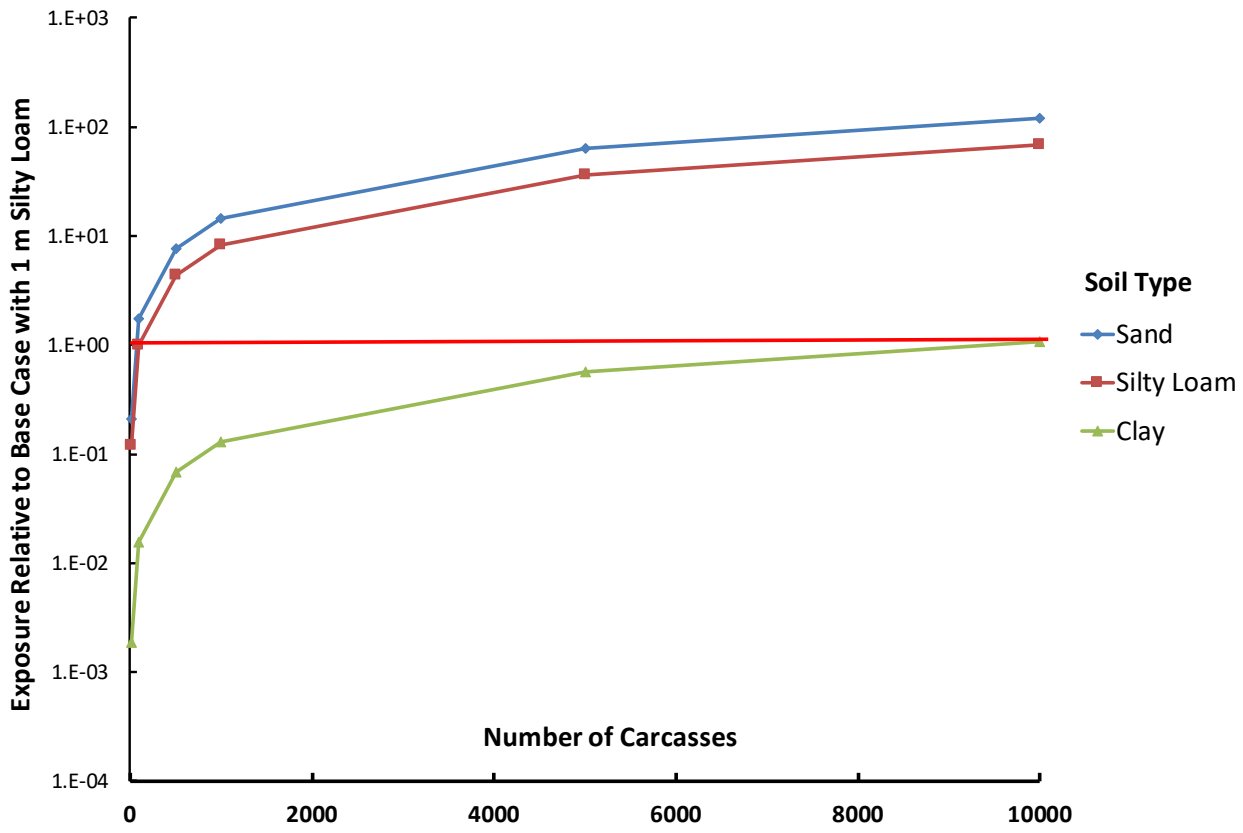

Figure 4-11. Uncertainty analysis for the number of carcasses, water ingestion exposure for dairy cattle by soil depth, relative to exposure with 100 carcasses and silty loam.

Exposures estimated with the two fastest decay rates (i.e., 1E+07 and 1E+08) are not included in Figures 4.12 through 4.14 because they are negligible (e.g., <1E-25).

The most sensitivity to the decay rates is seen with the two middle values, including the base case and rounded base case (1.0E-06). Exposures with these decay rates decline with soil depth, more so with clay than the coarser soils because the downward flow rate is slowest.

As with all of the decay results in this section, the travel time and amount of decay may be overestimated because the simple calculations to estimate travel time do not account for absorption-desorption processes, which retard their movement as demonstrated by the Virulo simulations in Section 3.2.4.

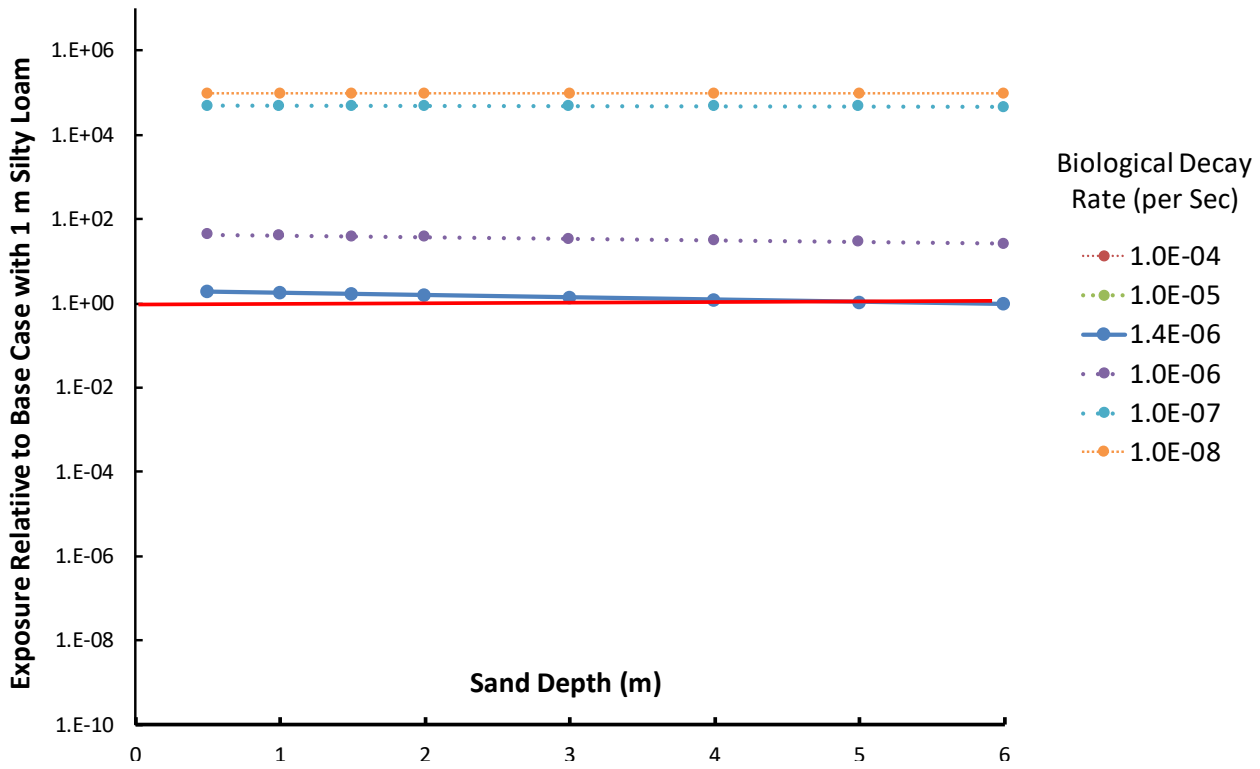

Figure 4-12. Uncertainty analysis for the biological decay rate, water ingestion exposure for dairy cattle by depth of sand, relative to exposure with 1 m silty loam.

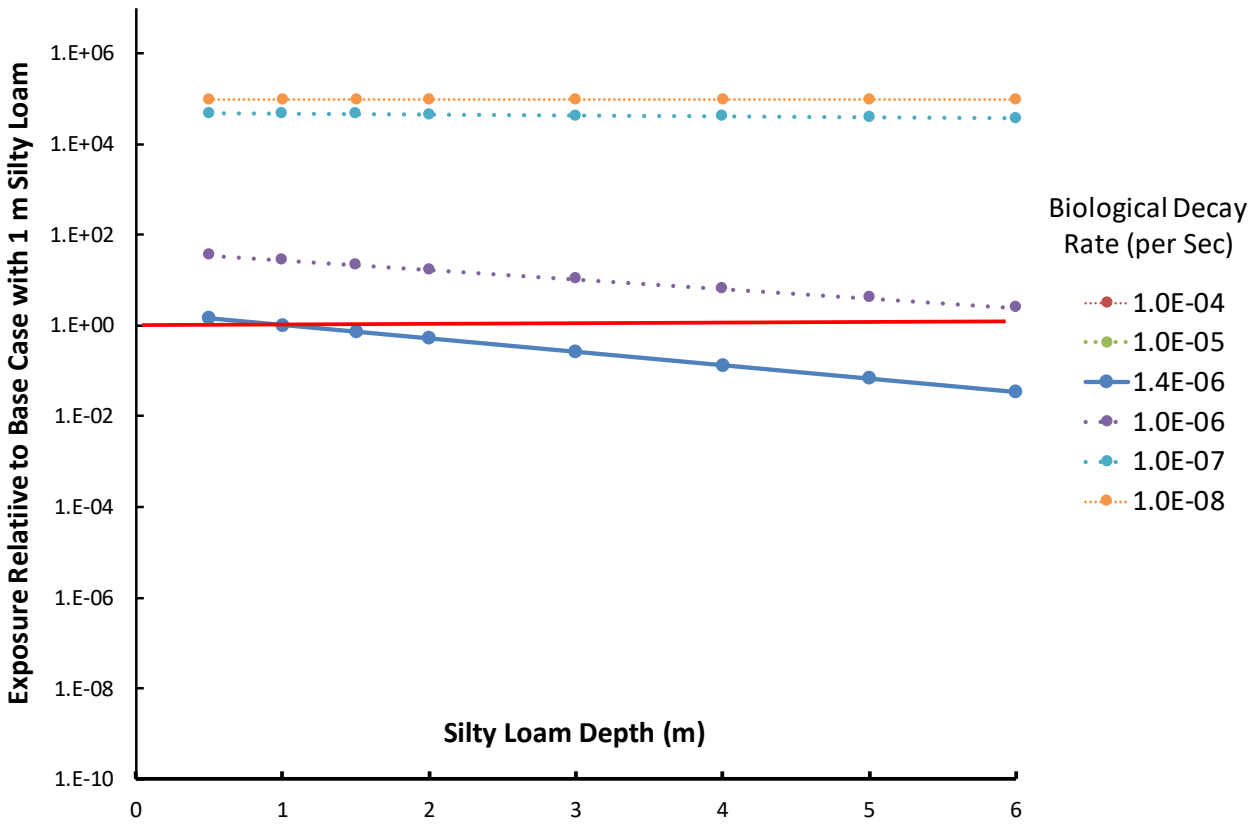

Figure 4-13. Uncertainty analysis for the biological decay rate, water ingestion exposure for dairy cattle by depth of silty loam, relative to exposure with 1 m silty loam.

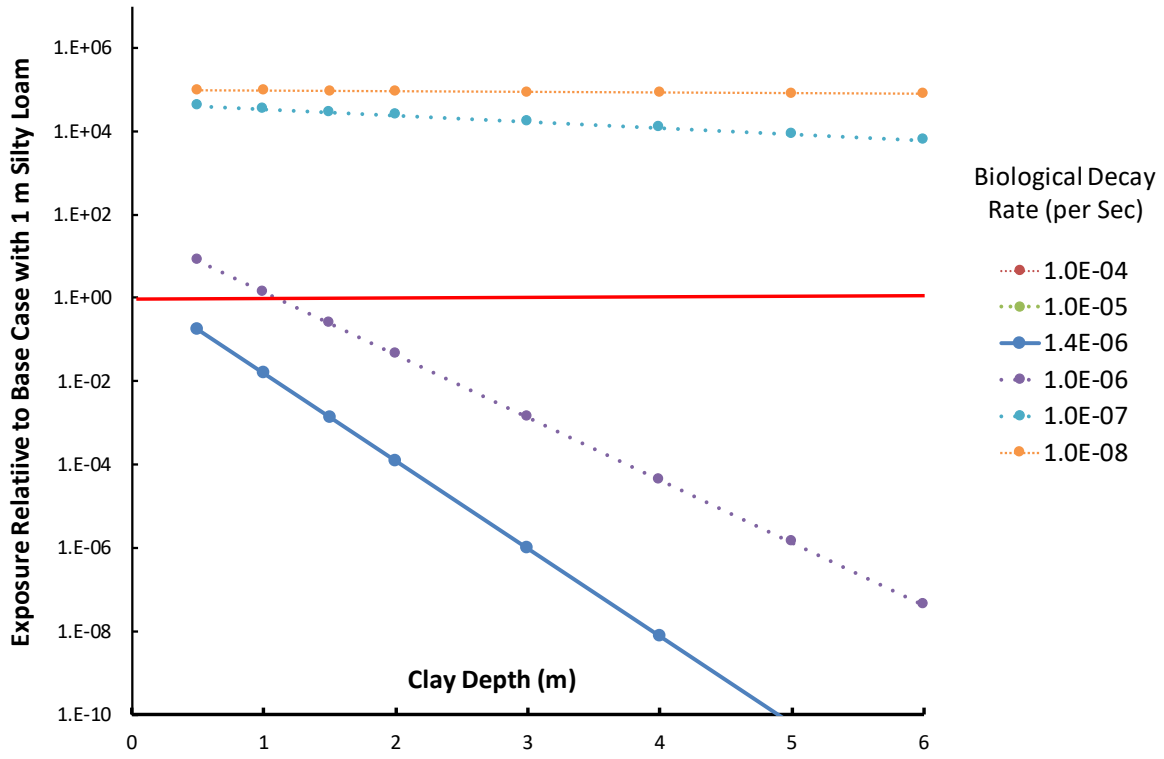

Figure 4-14. Uncertainty analysis for the biological decay rate, water ingestion exposure for dairy cattle by depth of clay relative to exposure with 1 m silty loam.

4.4 Uncertainty Summary and Research Needs

This section discusses how the exposure assessment might over- or underestimate exposures in the event of an actual FMD outbreak. Tables 4.7 through 4.9 summarize three types of "uncertainties" in the exposure assessment:

- Parameters with Moderate to High Natural Variation (Table 4.7)
- Uncertain Parameter Values or Models (Table 4.8)
- Simplifying Assumptions (Table 4.9)

This assessment necessarily involves numerous selections of values for a broad array of biological and environmental parameters, some of which are well characterized but vary substantially (e.g., by location within the United States), and some of which are unknown and require estimates from limited data (e.g., rates of FMDv release to air). The conceptual models for the carcass management options revealed that many direct and indirect multimedia exposure pathways could exist. To provide some quantitative basis for ranking the management options, many simplifying assumptions about the natural disaster, the types of and numbers of livestock killed, site and environmental conditions, and carcass management activities were required.

Table 4.7 describes parameters for which substantial variation exists across the United States, and a value was selected either to be nationally representative, to be health protective (i.e., overestimate exposure), or for another reason. The magnitude (low, medium, high) and direction (under- or overestimate) of bias in the exposure estimates are listed.

Table 4.8 describes parameters for which limited data were available to calculate a central tendency value or to estimate likely variation across conditions possible in the country. Uncertainty is characterized as low, medium, or high. By definition, the direction of bias is unknown.

Finally, Table 4.9 includes "simplifying assumptions" that were required to define the scope of the assessment and limit it to a reasonable level of effort. As for Table 4.7, the magnitude (low, medium, or high) and direction (under- or overestimate) of bias introduced by the assumption is summarized.

Based on the uncertainties in Tables 4.7 through 4.9, as well as information gathering for this assessment, Table 4.10 identifies research needs for the livestock carcass management options and associated activities.

Table 4-7. Moderate to High Natural Variation in Parameter Values—Potential Bias from Selected Values

Key Topic	Selected Parameter Value	Bias	Rationale
Scale of Mortality	▪ Base-case culling of 100 cattle at one farm with a total weight of 50 short tons to match previous analyses (APHIS 2015, USEPA 2017). ▪ Uncertainty analysis includes up to 10,000 culled cattle.	Possible Under-estimate	▪ The base-case number of cattle carcasses assumed for this assessment could be considered "small" because culling hundreds to tens of thousands of cattle might be required for a large FMD outbreak. Larger numbers of carcasses could involve larger temporary storage pile(s), increasing the chances of infecting one or more neighboring susceptible animals via inhalation. ▪ If ground surface area covered by the collection of carcasses into temporary storage pile(s) is proportional to the number of carcasses, leaching to ground water could occur over a larger area, but that would not increase FMD concentrations in ground water. ▪ Large scale losses of several thousand cattle could exceed the capacity of some management options (e.g., air-curtain burning).

Key Topic	Selected Parameter Value	Bias	Rationale
Ground water	▪ FMDv leached from the temporary storage pile and burial trench can reach ground water. Based on state regulations, ground water is assumed to be 1 m below bottom of buried materials or 1 m below the temporary storage pile. ▪ Layout Assumption: Neighboring cattle are provided water from a relatively shallow aquifer that flows in the direction of the neighboring well from the infected premises.	High Over-estimate	▪ Although providing livestock with drinking water with shallow ground water is possible, most wells are dug to tap into deeper aquifers that provide adequate water during the drier seasons as well as rainy seasons. ▪ Well contamination would require that the well is located down gradient (in the direction of ground water flow) from the source and that the rate of ground water flow is fast enough for viable virus particles to remain.
Meteoro-logical Conditions	▪ The assessment uses 1 year of meteorological data from a weather station in Iowa, chosen to represent a moderate climate in the U.S. agricultural heartland. The data are used to model fate and transport of releases to air.	Moderate Over- or Underestimate	▪ The meteorological data used for this assessment could over- or underestimate relevant conditions in other areas of the country (e.g., having stronger or weaker winds, winds predominantly in one direction compared with other patterns).

Key Topic	Selected Parameter Value	Bias	Rationale
Soil Type and Properties	▪ The assessment considers three soil types: two extremes (i.e., clay and sand) and one "middle of the road," silty loam. ▪ Clay-like soils comprised of fine particles can hold more water, but retard downward flow and adsorb a higher fraction of virus particles. ▪ Sandy soils allow rapid leaching of water and virus particles ▪ The assessment does not consider accelerated transport through macropores.	Moderate to High Over- or Underestimate	▪ Sites with different soil types and conditions could have higher or lower rates of vertical water movement and capacity to adsorb viruses. Although the three soil types were chosen to represent a range of conditions, other conditions are possible and transport though soil of a single type can vary due to soil density, homogeneity, and geohydrological factors. ▪ The exposure estimates for drinking water overestimate exposure because they do not include adsorption-desorption processes that retard the movement of the virus particles in soil. These processes are included in the Virulo modeling presented in Section 3.2.4. ▪ The presence of macropores would cause greater transport of virus to ground water than estimated. Where the ground-water system in question is connected to potential virus sources by karst, fractured rock, gravel, or a soil exhibiting preferential flow, there would be a high risk for viral transport to ground water.
Receptors	▪ Exposures are assessed for uninfected cattle on a neighboring farm. Inhalation and forage ingestion exposure are assessed for cattle at distances from 100 m to 10 km. No distance is specified for the ground water well.	Moderate to High Overestimate	▪ While uninfected cattle may be present within 10 km of the outbreak location, it is unlikely that uninfected cattle would be allowed at distances as close as 100 m.

Key Topic	Selected Parameter Value	Bias	Rationale
Exposure Factors	▪ Exposure factors (e.g., forage and incidental ingestion rates, drinking water rates) are from USEPA's HHRAP and other publications. The values used in the assessment are central tendency estimates.	Neutral	▪ Central tendency values are used so that exposure is not over or underestimated by this aspect of the approach.

FMD = foot and mouth disease; HHRAP = Human Health Risk Assessment Protocol

Table 4-8. Uncertainty in Parameter Value(s) Selected

Parameter	Description	Uncertainty	Rationale for Uncertainty Category
Releases Estimates	▪ Each exposure pathway in the assessment begins with a release of FMDv to an environmental medium. These include emissions to air from the temporary storage pile and liquid releases from the storage pile. Data to characterize amount and rate of viruses released from the carcasses are very limited.	High	▪ This is one of the most significant sources of uncertainty in the exposure assessment. Although release estimates were based on the best available information, releases might be over or underestimated. In addition, actual releases can vary significantly due to many factors (e.g., unit design, environmental conditions). The effect of this uncertainty is evaluated in the uncertainty analysis.
Animal Vectors	▪ FMDv can be transported by insects, birds, or mammals that come in contact with carcasses before or during management. The exposure assessment discusses but does not quantitatively evaluate animal vectors.	Moderate	▪ The exclusion of animal vectors from the assessment causes potential exposures to be underestimated. This uncertainty impacts the composting option more that burial or the combustion-based options.
Biological Decay Rate	▪ FMDv undergo natural decay that decreases the amount of viable virus over time. The assessment uses estimates of virus decay rates in air, soil, and leachate. Data to develop these estimates for the assessment are very limited. Moreover, the rate of decay is affected by a number of highly variable environmental conditions (e.g., ambient temperature, relative humidity, pH, ultraviolet exposure).	High	▪ The assumed decay rates are among the largest sources of uncertainty in the assessment. The base-case estimates are based on the best available information and the effect of this uncertainty is examined in the uncertainty analysis.

Parameter	Description	Uncertainty	Rationale for Uncertainty Category
Models	▪ The assessment uses screening-level models and calculations to estimate the fate and transport FMDv through air, water, soil, and vegetation.	High	▪ The uncertainties associated with fate and transport modeling data and methods can individually contribute to under-or over-estimation of exposures. In general, the assessment uses more conservative assumptions and approaches, which would most likely result in over-estimates of possible exposures. ▪ Because the approach uses pre-existing models and methods that were developed for different purposes, they are likely to differ in their level of sophistication and uncertainty. This could cause the level of uncertainty to differ among media pathways.
FMD Properties and Other Inputs	▪ Fate and transport modeling uses various properties of FMDv and environmental media (e.g., soil bulk density). Properties for environmental media are from HHRAP (USEPA 2005) unless otherwise noted.	Moderate to High	▪ Uncertainty associated with modeling inputs may contribute to over- or underestimation of exposure. This uncertainty is lowest for experimentally derived chemical properties and greater for more variable inputs.

FMDv = foot and mouth disease virus; HHRAP = Human Health Risk Assessment Protocol
Complete references are found at the end of this report.

Table 4-9. Simplifying Assumptions—Effects on Exposure Estimates

Key Topic	Simplifying Assumption	Effect	Rationale for Effect
Temporary Carcass Storage	▪ The assessment assumes that carcasses are placed in temporary pile for 48 hours during preparation for further management.	Moderate Overestimate	▪ Temporary storage is not a necessary feature of carcass management (e.g., if cattle are euthanized immediately prior to further management). The storage pile is included so that the assessment does not overlook releases that could reasonably be expected from a relatively uncontrolled source early after death.
Design of On-site Management Units	▪ Basic assumptions about the design of on-site management options (e.g., burial trench dimensions, storage pile assumptions) are based USDA guidance and other relevant sources. For larger mortalities, the unit design and spatial pattern could be different. ▪ The assessment assumes that the temporary storage pile is placed on bare earth.	Moderate Over- or Underestimates	▪ Assumptions about many aspects of carcass management units could lead to over- or underestimation of exposure. ▪ Exposures from the storage pile are overestimated if liquids released from the carcasses are collected and appropriately managed.
Carcass Handling Before Management	▪ Workers who handle livestock carcasses are assumed to use recommended PPE.	Moderate Underestimate	▪ Exposure to workers is underestimated if no PPE is used.
Exposure Pathways	▪ A goal of this assessment is to assess exposure for reasonably anticipated exposure pathways from carcass management. Therefore, the assessment was intentionally designed to include feasible complete exposure pathways that might not exist at some sites.	Moderate Overestimate	▪ The assessment is likely to overestimate exposure because the layout assumes a worst-case exposure for each possible pathway, which is unlikely at most locations.

Key Topic	Simplifying Assumption	Effect	Rationale for Effect
Virus Inactivation	▪ The assessment assumes that FMDv is not viable in most compartments of the carcass due to the low pH conditions that coincide with *rigor mortis*. However, some FMDv present in the bone, lymph nodes, liver, and kidneys could remain viable even after *rigor mortis*. Because remaining viable FMDv is further subjected to natural biological decay processes, releases after the 48-hour temporary storage pile are assumed to contain low concentrations of viable virus.	Low Underestimate	▪ Viable virus might persist after carcasses after they are placed in the burial trench or compost windrow. However, releases to soil from the burial trench would be the same or less than releases from the storage pile during the period of greatest liquid releases. The windrow provides greater containment of liquid, and both of these management options contain air releases more than the storage pile.
Carcass Transportation	▪ Based on a semi-quantitative assessment during the natural disaster scenario assessment, exposures associated with carcass transportation are assumed to be insignificant.	Low Underestimate	▪ Carcass transportation would follow biosecurity measures under the FMD response plan.
Livestock Grazing	▪ Uninfected livestock are assumed to graze at the location of greatest estimated virus deposition from the air.	High Overestimate	▪ In the event of an actual FMD outbreak, it is unlikely that uninfected livestock would be pastured in close proximity to the outbreak location.

Table 4-10. Research Needs for Livestock Carcass Management Options and Activities

Option or Activity	Research Needs
On-site Combustion	▪ Monitoring or analysis to verify complete destruction of FMDv, and other viral agents, in air emissions and ash.
On-site Burial	▪ Systematic study to determine survival of FAD agents such as spore-forming microbes and viruses during carcass decomposition. ▪ Identification of microbes in leachate from burial of FAD agent-infected carcasses. ▪ Research on distribution of FMD viral load across organs and tissues in infected livestock. ▪ Additional field studies of subsurface movement and survival of FAD agents in various soil types and seasons. ▪ Develop model of time-varying addition of viral particles to surface soil that predicts concentration of viable virus units likely to reach ground water for specified precipitation events, different soil saturation conditions, and different temperatures.
On-site Composting	▪ Studies of pathogenic microbes in finished compost. ▪ Field analysis of the fate and transport of pathogenic microbes during composting and following application of compost to surface soil. ▪ Overnight surveillance (e.g., motion-activated wildlife cameras) to compile data on nocturnal scavenger activity around compost piles.
Off-site Options	▪ Survey facilities to find any that might have accepted FMD-infected cattle during past outbreak. Evaluate information recorded during the incident. ▪ Design monitoring studies for off-site facilities to implement in the event of an FMD outbreak in the United States.
Carcass Handling	▪ For a quantitative exposure assessment, data on exposure factors (e.g., frequency and duration of hand contact, area of skin exposed) for carcass handlers, and the effectiveness PPE or likely compliance with PPE use. ▪ Concentrations of FAD agents on contact surfaces. ▪ Explore the role of common items (e.g., vehicles, worker clothing, etc.) as fomites and best practices for decontamination or "disposal" of contaminated materials after the response actions.
Temporary Carcass Storage	▪ Monitoring air downwind of uncovered storage piles for viable microbes. ▪ Analysis of microbial load on fur or feathers of livestock soon after culling. ▪ Research to better characterize the biological decay of FAD agents in livestock carcasses.

	▪ Collect leachate from freshly killed carcasses daily over one or two weeks at different temperatures. ▪ Assay leachate for viable microbes over time.
Carcass Transportation	▪ Further research to measure or estimate microbial releases associated with transporting carcasses to off-site facilities.

FAD = foreign animal disease; FMD = foot and mouth disease; FMDv = foot and mouth disease virus; PPE = personal protective equipment

4.5 Summary of Findings

This assessment is meant to support selection of environmentally protective livestock carcass management methods in the event of an FAD outbreak. This exposure assessment addresses only one FAD agent, FMDv. For this agent, FMD exposure is most likely to result from activities in the first hours and days after death because:

- FMDv does not replicate outside a living host, and the amount of viable FMDv will decline after death due to natural decay processes.
- Within most compartments of a carcass, the viability of FMDv significantly decreases along with a decrease in pH that coincides with *rigor mortis*.

It is important to remember that the findings for FMDv exposures in the assessment are not necessarily applicable to other FAD agents, particularly non-viral microbes such as bacteria and protozoa. In addition, this assessment concerns exposures to individual animals from the air they breathe, water they drink, and the forage they graze. It does not address the spread of infection among animals within a herd.

FMD exposure are estimated using generally conservative scenarios and assumptions that would overestimate exposures at most actual carcass management locations. Section 4.4 identifies and discusses uncertainties and assumptions in the assessment. This information can be used to evaluate exposure scenarios and the potential for exposure to occur at actual sites.

Key findings of the assessment are presented below, organized by management option and related activities.

Temporary Carcass Storage

- If carcasses cannot be managed immediately after death, the temporary carcass storage pile appears to be the most likely source to possibly expose nearby livestock.
- Inhalation is the most likely cause of exposure because airborne virus particles can be travel more quickly and with fewer barriers compared to the ground water pathway.
- If the storage pile is placed on bare earth, exposure to cattle through drinking water is possible. However, a number of conditions (e.g., a well is in the direction of ground water flow) must be met for a complete exposure pathway, which is unlikely at many sites.
- If the soil depth to ground water is at least 1 m, there is a high probability that at least 99.99% of FMDv particles attenuation before leachate reaches the water table.
- The potential for exposure is affected by several site-specific factors and uncertainties discussed in Section 4.4. The uncertainty analyses in Section 4.3 examines how the exposure estimates change with varied virus release rates, biological decay rates, soil types and depths, and numbers of carcasses.
- Exposures through air and ground water can be mitigated with tarps or other barriers beneath and over the storage pile.

On-site Open Burning and Air-curtain Burning

- On-site combustion options effectively destroy FMDv when there is an even burn (i.e., all soft tissues are burned).

- Because FMDv is inactivated by combustion, exposures were not estimated for these management options.

Composting

- Composting provides thermal treatment and containment. Thermal inactivation and natural decay essentially eliminate potential exposure from the finished compost. The compost can be kept in the windrow until infective FMDv is not detected.
- Although composting is an effective option for FMDv, this is not necessarily the case for other FAD agents. Prions and environmentally resistant life stages (e.g., spores of spore-forming bacteria such as anthrax) might not be completely inactivated by composting.

On-site Burial

- Burial provides containment only, and FMDv has the potential to leach through soil to ground water similarly to the temporary storage pile. However, soil at least 1 m deep will provide a high level of attenuation and several conditions must be met for there to be a complete exposure pathway.
- Unlike the temporary storage pile, there would be no exposure from inhalation or ingestion of forage and soil.
- The potential for exposure through the ground water pathway is reduced if carcasses are placed in the trench after *rigor mortis*. However, overall exposure from carcass management could be greater depending on how the carcasses are managed before *rigor mortis*.

Carcass Handling and Transportation

- Adherence to biosecurity measures (e.g., vehicle decontamination) and the use of PPE recommended by USDA/APHIS (USDA 2014a), as assumed for this assessment, mitigates human exposure to FMD and the potential for workers to spread FMDv.
- Based on an evaluation in USEPA (2017), exposures during carcass transportation are assumed to be negligible at locations along the transportation route. Using federal transportation statistics and a scenario in which eight truckloads of carcasses are transported 100 km, USEPA (2017) estimated risk of an accident with cargo spillage to be 7.1E-05.

Off-site Carcass Management Options

- Among the three off-site options, commercial incinerators would totally inactivate FMDv, and rendering facilities similarly apply sufficient heat for enough time to inactivate the virus, viable FMDv in carcasses placed in landfills could contribute to leachate, however livestock are not likely to come in contact with the leachate collected and managed under regulatory requirements. For all the off-site options, all releases to the environment (e.g., incinerator emissions to air, rendering facility discharge to surface water) are restricted by, and are assumed to comply with, normally applicable federal regulations. For these reasons the off-site options are not included in the quantitative assessment.

Table 4.11 ranks on-site management options based on the exposure assessment and the degree to which treatment or containment control releases of FMDv to potential exposure pathways. The

temporary carcass storage pile is included in the rankings even though it is not a management option and can be used before any of the on-site or off-site management options. It is included because releases from to air or the ground could cause higher potential exposures than any of the management options.

Off-site management options are not included in Table 4.11 because they are not included in the quantitative assessment, as discussed in Section 2.2. As part of the exposure assessment for the natural disaster scenario (USEPA 2017), the off-site options were qualitatively ranked relative to each other for control of microbes based on their level of thermal destruction. Those rankings are shown in Table 4.12.

Table 4-11. Ranking of On-site Livestock Carcass Management Options for an FMD Outbreak

Rank	Management Type	Principal Rationale
1	Open Burning and Air-curtain Burning	Thermal descruction of all FMDv.
2	Composting	Bulking material contains almost all FMDv from releases to air and soil. Thermal inactivation and biological decay eliminate FMDv before composting is complete.
3	Burial	Cover soil contains releases to air. If a number of conditions are met, leaching has the potential to infect cattle that drink water pumped from a ground water well.
4	Temporary Storage	Cattle can be infected by inhaling or ingesting FMDv emitted to air from a nearby storage pile. If a number of conditions are met, leaching has the potential to infect cattle that drink water pumped from a ground water well.

FMDv = foot and mouth disease virus

Table 4-12. Ranking of Off-site Livestock Carcass Management Options for Microbes

Rank[a]	Management Option	Principal Rationale
H	Off-site Incinerator	Thermal destruction of all microbes, ash is landfilled
M	Off-site Rendering	Thermal inactivation of all microbes except prions, workers protected from prion exposure with the use of PPE
L	Off-site Landfill	Containment, including liner, leachate collection, cover material, but no thermal destruction; when capacity is reached, landfill is closed and new ones built

Abbreviations: H = Highest rank; L = Lowest rank; M = Middle rank; PPE = personal protective equipment.
[a] Relative and absolute risks from microbial pathogens depends on initial concentrations in healthy cattle, which is unknown.

In the event of an actual FAD outbreak, site managers can use this report with site-specific information and properties of the FAD agent to identify possible exposure pathways, determine

whether complete exposure pathways actually exist, and how exposures can be avoided. The following information provided in this report can aid such evaluations.

- **Conceptual models** – Conceptual models for the temporary storage pile and on-site burial are included in Section 2.4. These identify the possible pathways by which cattle might be exposed to the FAD. Conceptual models for all of the carcass management options and associated activities (e.g., carcass handling, transportation) are available in the exposure assessment of livestock carcass management options following natural disasters (USEPA 2017).
- **Environmental fate concepts** – The descriptions of FMDv releases and environmental fate estimation in Section 3 identify factors (e.g., temperature and humidity aquifer, water well characteristics) that determine whether a complete exposure pathway actually exists at a particular site.
- **Management option assumptions** – Sections 3.2 and 3.3 and USEPA (2017) provide information (e.g., management option specifications) compiled from the literature that may be useful for site-specific assessments.
- **Biological decay estimation** – The report provides equations to calculate biological decay and describes how decay relates to the management options.
- **Variability relationships** – Section 4.4, as well as topics discussed throughout the report, describe how exposures might differ at sites where scenarios and assumptions differ from those assumed for this assessment.
- **Mitigation** – By describing the environmental releases and exposure pathways for the management options, the report can be used to identify effective mitigation measures to prevent or reduce radiation exposure.

5. Secondary Data

This report used scientific information extracted from sources of secondary data including journal articles, publications in the open literature, and government reports both published and non-published, including distribution limited reports. Data and information were gathered from published reports to identify the significant pathways by which pathogens might reach individuals and estimate how many microorganisms an individual is likely to be exposed to through each pathway. A targeted literature review was performed to identify the most highly relevant data to inform an exposure assessment. Scientific and technical information from various sources were evaluated using the assessment factors below:

- Focus: The extent to which the work not only addresses the area of inquiry under consideration, but also contributes to its understanding; it is germane to the issue at hand.
- Verity: The extent to which data are consistent with accepted knowledge in the field, or if not, the new or varying data are explained within the work. The degree to which data fit within the context of the literature and are intellectually honest and authentic.
- Integrity: The degree to which data are structurally sound and present a cohesive story. The design or research rationale is logical and appropriate.
- Rigor: The extent to which work is important, meaningful, and non-trivial relative to the field. It exhibits sufficient depth of intellect rather than superficial or simplistic reasoning.
- Soundness: The extent to which the scientific and technical procedures, measures, methods, or models employed to generate the information is reasonable for, and consistent with, the intended application.
- Applicability and Utility: The extent to which the information is relevant for the intended use.
- Clarity and Completeness: The degree of clarity and completeness with which the data, assumptions, methods, QA, and analyses employed to generate the information are documented.
- Uncertainty and Variability: The extent to which variability and uncertainty (quantitative and qualitative) related to results, procedures, measures, methods, or models are evaluated and characterized.

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