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Decision and Modeling Strategy for a Radiological Risk Assessment at Area G, Los Alamos, New Mexico – 17258

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ABSTRACT

The U.S. Department of Energy (DOE) owns a low-level radioactive waste (LLW) disposal site at Material Disposal Area G, in Los Alamos, New Mexico, USA. Area G has been the primary LLW disposal site for Los Alamos National Laboratory (LANL) since the 1960s, and is now approaching the end of its service life. In addition to LLW, Area G is host to a variety of other wastes, the disposition of which must be determined before closure of the site. A probabilistic Radiological Risk Assessment (RRA) for Area G is used in order to support decision making regarding some wastes that are not addressed in the extant Area G Performance Assessment (PA) and Composite Analysis (CA).

Between 1979 and 1987, 33 special shafts were augered into the Bandelier Tuff at Area G. This tuff is present across Pajarito Plateau on the eastern slopes of the Jemez Mountains, and varies widely in its consistency, from weakly indurated non-welded layers to welded layers that uphold the mesa cliffs of the Plateau. These mesas are home to LANL, Area G, and the town of Los Alamos. The 33 Shafts were lined with steel casing, and contain remote-handled (RH) transuranic wastes (TRU) resulting from experiments and analysis performed in special glove boxes at the Chemistry and Metallurgy Research (CMR) facility at LANL. Some of these wastes originated as used ("spent") nuclear fuel.

The purpose of the Area G RRA is to evaluate the potential future risk to humans and the environment from the RH TRU in the 33 Shafts in the context of the risk associated with the surrounding wastes at Area G. The analysis is responsive to expectations outlined in DOE Order 458.1, *Radiation Protection of the Public and the Environment*, and is informed by the Manual and Guidance accompanying DOE O 435.1, *Radioactive Waste Management*. Because the waste meets the definition of TRU, the regulatory context also takes into consideration the regulation governing the disposal of TRU from the U.S. Environmental Protection Agency (EPA): 40 CFR 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*.

Given the broader regulatory context for the RRA, the analysis is subject to different assumptions from those made in the existing DOE O 435.1 PA and CA, such as allowing for future occupation of the site. The analysis begins with a comprehensive evaluation of features, events, processes, and exposure scenarios (FEPS) for Area G and the wastes it contains. These FEPS are screened to eliminate from further consideration those of extremely low probability and/or consequence, and a conceptual site model (CSM) is subsequently developed. The scope and structure of the Area G RRA Model is informed by this CSM, and the Area G RRA Model is developed using the GoldSim systems analysis modeling platform.

This paper outlines the development of a defensible, transparent, and reasonably realistic model, which is based on the state of knowledge of the wastes, the site, and the FEPS that govern contaminant transport and human exposures. Probabilistic model input distributions represent uncertainties inherent in the real and modeled systems. The results of the Area G RRA Model will inform decision analysis regarding the disposition of the RH TRU in the 33 Shafts.

INTRODUCTION

The principal radioactive waste disposal facility for Los Alamos National Laboratory (LANL) is Material Disposal Area (MDA) G, or Area G. Area G is located within Technical Area (TA)-54, on Mesita del Buey on the LANL campus, and first accepted disposal of radioactive waste in 1957 [1]. A satellite image of the region is shown in Fig. 1. At the time, there was no regulatory distinction between low-level radioactive waste (LLW), transuranic waste (TRU) or other contemporary classifications of radioactive waste. In 2017 Area G is nearing the end of its service life, with closure is on the horizon. Certain waste issues are in need of resolution before closure can be completed. Both the property and the waste in Area G are owned by the U.S. Department of Energy (DOE).

One problematic collection of wastes is known as the "33 Shafts," which are numbered 200 through 232. Most of the shaft casings have a diameter of 30 cm or less, and a total length of 4 m or less, with the top of the casing within a meter of the ground surface. Shaft 212 contains the vessel for an experimental reactor (the Los Alamos Molten Plutonium Reactor Experiment, or LAMPRE) and the other 32 contain wastes from irradiated nuclear reactor fuel examinations in LANL's Chemistry and Metallurgy Research Wing 9 [2]. Waste generator records and other historical records indicate that the bulk of these wastes consist of ^{235}U, ^{239}Pu, and mixed fission products (MFPs), conforming to the description of remote-handled (RH) TRU. The 33 Shafts were constructed and filled from 1979 through 1987.

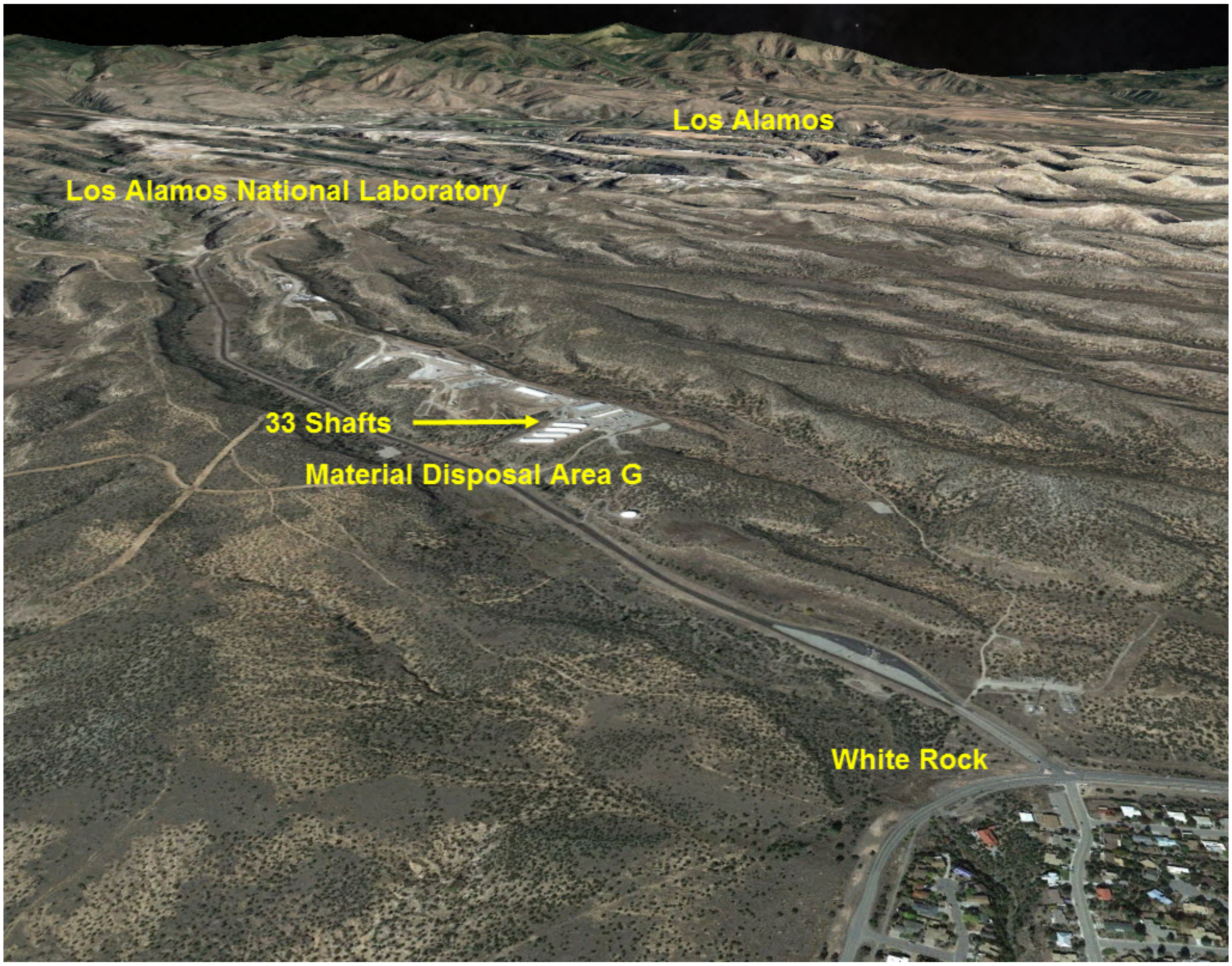

Fig. 1. Location of Area G relative to LANL and population centers.

Mesita del Buey is a flat-topped mesa created by voluminous eruptions of tuff and subsequent erosion to form the prominent cliffs and stream-carved valleys and canyons typical of Pajarito Plateau, the home of both LANL and the County of Los Alamos, New Mexico. Because the 33 Shafts were emplaced after the 1970 ban on near-surface disposal of TRU [3], they would have been installed with the understanding that they would be retrieved at some point, and so did not need to meet the siting guidelines for wastes purposefully disposed at Area G. In particular, they did not have to be located at a minimum distance of 15 m from the cliff edge. The 33 Shafts are located in a part of Area G that is partly bermed with crushed tuff fill, making it more susceptible to erosion than the more competent intact tuff that surrounds most of the other waste units.

Decision makers wrestling with the ultimate disposition of the 33 Shafts have a challenge. Although Immediate Action Directive (IAD) No. 0155-21 [3] clearly indicates that any TRU wastes generated after 1970 must be dispositioned in a retrievable manner, extenuating circumstances complicate their retrieval. Even though the total material at risk (MAR) for the 33 Shafts is thought to be less than 3.7 plutonium-equivalent TBq (100 plutonium-equivalent Ci), the worker risks involved in removal and treatment of the RH TRU are highly uncertain, and project costs and technical execution complexity are both considered to be very high [4]. Consequently, DOE’s Office of Environmental Management and the National Nuclear Security Administration (NNSA) are considering alternative approaches to the disposition of the 33 Shafts, ranging from closure in place with a regulatory exemption to complete excavation, treatment, and disposal as TRU waste in a geologic repository as required by current regulations.

Such decisions require analyses addressing future risks to human health and the environment and other factors such as worker risks, public acceptance, transportation risks, terrorism risks, and costs. The subject of this paper is the Area G Radiological Risk Assessment (RRA), which is being developed to address the first of these issues: assessing future risks to the public, and to ecological systems.

REGULATORY CONTEXT

In the 1950s and 1960s, disposal practices were more primitive than they are today [5]. In 1970, the Atomic Energy Commission (AEC, which later became the DOE and the U.S. Nuclear Regulatory Commission, or NRC), issued IAD No. 0155-21 [3]. The IAD required that “wastes with known or detectable contamination of transuranium nuclides [be] packaged and buried in such a fashion that they can be readily retrievable...” This applies to the wastes in the 33 Shafts, since their emplacement post-dates the IAD. A complicating factor is that, despite this Directive, concrete was poured into the annulus of some of the Shafts, making retrieval more difficult. If costs and the potential risks from waste retrieval were not significant, the obvious path forward would be to remove the wastes from the 33 Shafts, which would likely involve removing each entire shaft and the associated casing, corrugated steel pipe, and concrete. The waste would then be processed for disposal at a deep geologic repository such as the Waste Isolation Pilot Plant (WIPP). Such a decision, however, should also be informed by the nature of future risks potentially posed from leaving the wastes in place, regardless of the regulations. Providing this information is the purpose of the Area G RRA.

Decision support includes the examination of other pertinent radioactive waste regulations, as well. The primary regulation for DOE wastes is DOE Order 435.1, *Radioactive Waste Management* [6], and its associated Implementation Guide [7] and Manual [8]. DOE O 435.1, however, is focused on the disposal of LLW, and defers the regulation of disposal of TRU waste to EPA’s Code of Federal Regulations (CFR) Title 40 Part 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes* [9, 10] (40 CFR 191). This regulation is oriented specifically toward geologic disposal, given the issuance of IAD 0155-21 [3], so its application to the possible disposal of TRU waste in the near surface is problematic. Nevertheless, some near-surface disposals of TRU at DOE sites have been evaluated and approved [11], and an evaluation of compliance of the 33 Shafts to 40 CFR 191 has also been developed [12]. These evaluations show that near-surface disposals have difficulty meeting the Containment Requirements of Part 191, for which it must be demonstrated that only a small fraction of the waste be released to the accessible environment within 10,000 years. While geologic repositories might meet this criterion, it must be recognized that near-surface disposal of TRU and the intent of 40 CFR 191 are conceptually incompatible. Near-surface disposal is outside the envelope of possibilities considered in the regulation. DOE O 435.1 is also not directly applicable, because the 33 Shafts do not contain LLW. The only regulatory path that allows the 33 Shafts to remain in place is to obtain a waiver by the Administrator of the EPA. That would require at least a substantive and defensible risk assessment such as the Area G RRA. The approach of performing a risk assessment to inform decision making is the principal message from the National Academies in their book *Risks and Decisions About Disposition of Transuranic and High-Level Radioactive Waste* [13]. Waste classifications (like TRU) should not by themselves determine unacceptable future risk.

DOE O 458.1-1, *Radiation Protection of the Public and the Environment* [14], however, clearly applies to Area G, and indeed to all the waste disposal facilities operated by the DOE. This Order is considered a primary guiding document for evaluation of risks, including future risks, for Area G, including the 33 Shafts. This order contains performance objectives that are different from those in either DOE O 435.1 or 40 CFR 191.

DOE O 458.1 requires, among other things, an explicit goal of keeping doses as low as reasonable achievable (ALARA). A population dose assessment is therefore required in order to minimize doses to the population, and not just to hypothetical individuals. The Order also requires an ecological risk assessment, which is not required by either DOE O 435.1 or 40 CFR 191. Perhaps most important, DOE O 458.1 does not presume the artificial and unrealistic constraints of perpetually effective institutional controls, and of a limited time of compliance. The RRA, which also does not recognize such constraints, is therefore targeted toward accurate assessment of human health and ecological risk, which is more useful for transparent and defensible decision making than is a traditional PA based on the carefully constrained performance objectives of DOE M 435.1-1 IV P (1) [8].

DECISION CONTEXT

As introduced above, the decision analysis that is to be informed in part by the RRA involves the consideration of several alternatives for disposition of the 33 Shaft wastes, with different objectives to weigh for each alternative. The RRA will provide critical information about potential future risk to human health and the environment, but other factors are also of interest to decision makers. The RRA makes no assumptions about specific regulatory criteria, such as the potential applicability of 40 CFR 191 or DOE O 435.1, but it does provide information that can be used in an evaluation with respect to those regulations for the purposes of comparison.

Potential objectives include minimizing human and ecological risks, and minimizing costs and worker doses. Alternatives range from leaving the 33 Shafts in place, to removing them for eventual treatment and disposal [15]. The close-in-place option could apply to some or all of the shafts, and those left in place would become part of the greater closure effort for all of Area G. Modeling this alternative involves consideration of the overall closure plan for Area G. Similarly, the alternative of *in-situ* remediation of some or all wastes would involve leaving them within Area G, though with additional barriers to short-term migration of the wastes into the environment. Remedial technologies could include vitrification, mixing with grout, or the installation of robust barriers to radionuclide transport. Shafts subject to such remediation would also be incorporated into the closure of all of Area G. Any wastes closed in Area G would be subject to analysis under an updated closure PA/CA, which would be responsive to both DOE Orders 435.1 and 458.1 [16].

At the other end of the range of alternatives, the 33 Shafts could be removed from their current location and transported to a facility that could handle their physical bulk and dimensions, and where they would be processed and packaged for disposal at a geologic repository. At this time, the only such facility that exists is at Idaho National Laboratory. This alternative would allow Area G to be closed and a PA/CA to be developed without taking into account the 33 Shafts. This is the assumption made in the current Area G PA/CA [17], so there would be no disruption of that ongoing process.

Removal and processing of any of the shafts will incur worker risks, which are highly uncertain [4, 18]. Transportation risks would be incurred while moving the 33 Shafts to a processing location, and again to the disposal site. An evaluation of such risks is also required in order to inform rational decision making and to address public concerns. Costing of any of the alternatives will be complex, and should account for uncertainties and potential overruns that are inherent in such large government projects.

Public acceptance of the decision may also be an important consideration. Stakeholders in northern New Mexico include eight major Native American Pueblos, rural landowners, and the population centers of Española, Los Alamos, Jemez Springs, Taos and Santa Fe. Other stakeholders include numerous Federal and State agencies, local hospitals and police, and the public along transportation corridors. Gaining public trust is advanced by engaging in transparent and defensible decision making.

A probabilistic decision model could also be developed in support of this larger analysis. A prototypical model has already been constructed [19], and could serve as a basis for developing a full-fledged, transparent, and defensibly parameterized model.

THE RADIOLOGICAL RISK ASSESSMENT

The role of the RRA in supporting decision making for the disposition of the 33 Shafts is to estimate the risk reduction of removing (or treating in place) some or all of the waste in the 33 Shafts. It is natural to consider this risk in the context of the risks form all radioactive wastes disposed at Area G. Representative questions include, “What is the relative difference in risks from Area G with or without the 33 Shafts?” and “Does this difference justify the costs, in terms of money and the risks inherent in the removal, transportation, treatment, and disposal of the wastes elsewhere?”

RRA development begins with the identification of features, events, processes, and exposure scenarios (FEPS) that are relevant to determining the potential future risks from the 33 Shafts. The FEPS that apply to the natural behavior of Area G and the human behaviors of potential future receptors must be determined so that a sufficiently comprehensive conceptual site model (CSM) can be constructed. This CSM is the foundation of subsequent modeling work, which involves the derivation of mathematical models to represent the influence of the various FEPS, the parameterization of those models with uncertain values that adequately reflect our state of knowledge, and the construction of a computer model to solve the system of equations quickly and efficiently. A generalized diagram of the conceptual model is shown in Fig. 2.

Like the PA/CA for Area G [17] that is developed to be responsive to the performance criteria in DOE O 453.1, the RRA is based on a model of Mesita del Buey and the radioactive waste facilities within it. Many of the basic features and processes are modeled similarly in both the PA/CA and the RRA, including the Bandelier Tuff and underlying geologic strata, diffusion in pore air, advection-dispersion and diffusion in pore waters, surface water and sediment transport, regional atmospheric dispersion, and biotically-induced transport mechanisms.

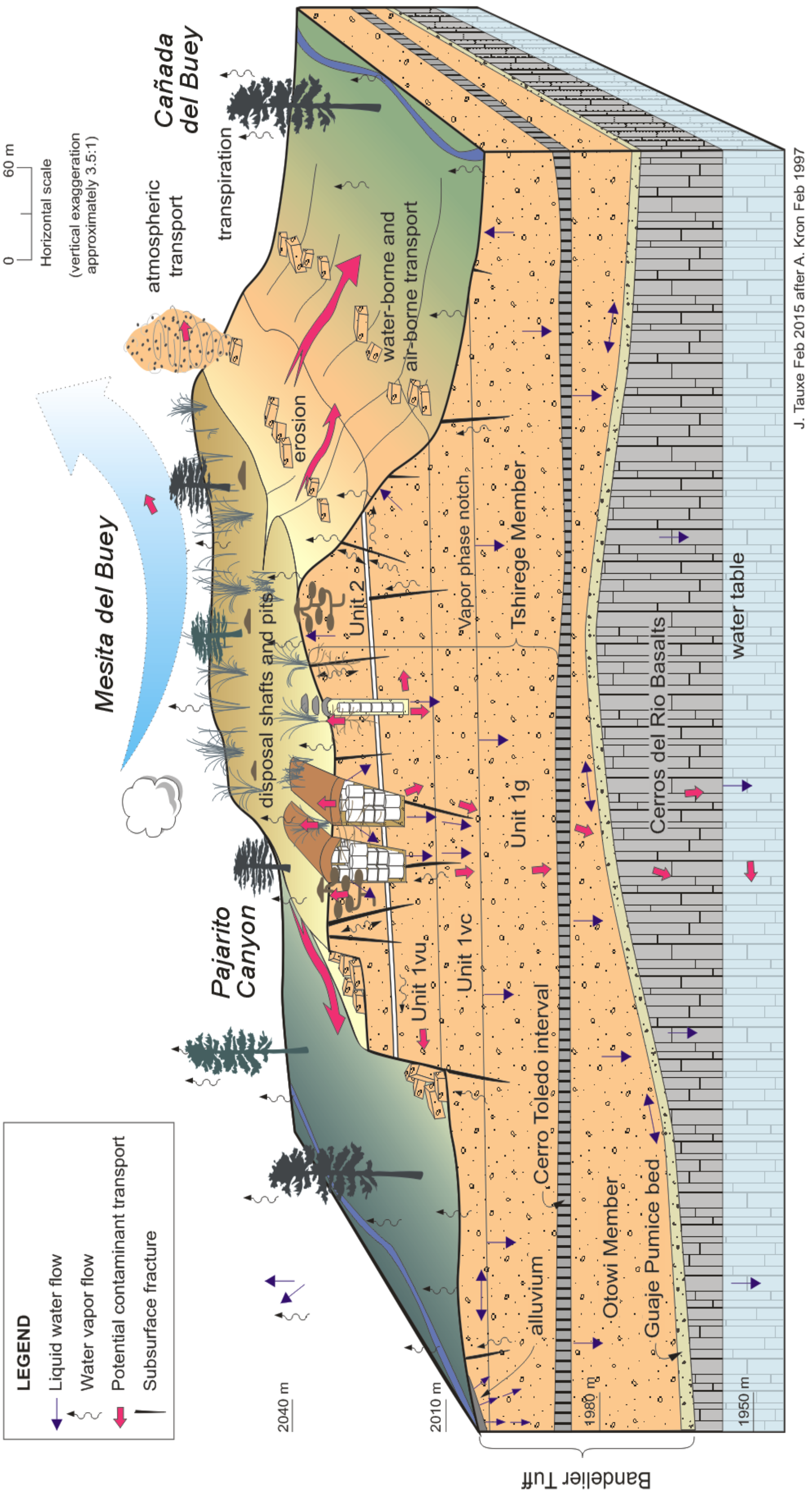

Fig. 2. Generalized conceptual site model of Area G at LANL.

The parameterization of the RRA modeling is different from that of the PA/CA, however, for several reasons. The time frame of interest is different, since DOE O 458.1 has no limit on the time of compliance. Looking past 1000 years into the future changes what needs to be included in the model. For example, the progressive failure of the Bandelier Tuff moves the mesa edge towards the waste disposal units in a process known as cliff retreat. In assessments concerned with compliance periods of only 1000 years, this process has been dismissed, but the RRA does not have this luxury. Eventually wastes will be exposed, so one purpose of the model is to evaluate the timing of this exposure relative to the natural change in risk (not always a reduction) due to radionuclide decay and ingrowth. A further matter related to erosion is the location of the 33 Shafts, located in an area where they are likely to be exposed before most other wastes at Area G, which are generally sited further from the cliff edge. This is an example of how FEPS can change if the timeframe of interest changes.

The derivation of some stochastic model input parameters is likewise time dependent, as described in *Statistical Methods for Effective Spatial and Temporal Scaling in Support of Probabilistic Performance Assessments* [20]. For example, an average precipitation rate over a short period is different from an average over a long period. Similarly, long-term average groundwater flow rates may be different from short-term rates. As long time frames are considered, the effects of climate change also need to be taken into account (see *Representation of Global Climate Change in Performance Assessment Models for Disposal of Radioactive Waste* [21]).

Appropriate spatial scaling also must be done with care, so as not to overestimate uncertainty. This is also discussed in detail in the *Statistical Methods* paper [20]. In spatiotemporal averaging, the parameter of interest is not simply the value of a property (for example, porosity) at a discrete point in space and time. Since the value is applied at all points and for all time in the model, what is needed is the average value over that space and time. The stochastic model input, therefore, must be a distribution of the average value, not simply a distribution of values of site data or those found in the literature.

Another consideration for model development in support of decision making is the matter of selection of model inputs that intentionally bias results one way or another. Before the advent of inexpensive and more capable computers and modeling platforms, PAs were generally designed to give "conservative" results—that is, input parameters would be deliberately chosen so as to produce doses or risks more extreme than their expected value. There are two fundamental flaws with this approach, although it is still used by some practitioners. First, it becomes apparent upon studying these models that what may cause higher doses (for example) for one pathway generally produces lower doses for another, or even affects the model in unexpected ways. The lesson learned is that one's intuition about what may be "conservative" is often flawed. Second, biased inputs produce biased outputs, which impedes rational decision making. Decision makers need models that reflect, to the extent possible, realistic outcomes. It is important that they grasp the context of where a result is in the realm of possibilities, rather than to base a decision on a result that is very unlikely. It is a policy judgment for the decision maker to make a conservative decision, but that decision should be based on realistic information.

Stochastic model inputs for the Area G RRA, therefore, are based on realistic values, with associated realistic uncertainty. While site-specific information is best, practitioners must often rely on experimental results obtained by others, literature reviews, and expert opinion. The combination of this diverse information into a stochastic distribution that captures the state of knowledge, including uncertainty, must be done with care. One example of such a derivation considers the development of geochemical parameters, including distribution coefficients, diffusivities, aqueous solubilities, and the like. This is described in detail in *Realistic Geochemical Parameter Uncertainty for Performance Assessment Modeling* [22].

The derivation of stochastic model inputs applies to more than physical model parameters. Human activities and behaviors are generally more uncertain than the parameters representing engineered features or natural phenomena [23-25]. The estimation of human activities at Area G is complicated by the diverse history of human occupation on Pajarito Plateau. Over the past millennium, there were times of relatively dense population by Puebloans in the Chaco period, followed by sparse seasonal occupation. In the decades before the Manhattan Project, homesteaders farmed the flat mesatops [26]. Today, Los Alamos County, immediately adjacent to the LANL campus, has a population of 18,000 persons. It is clear that the Plateau has undergone many different types of occupation, and there is no reason to expect that it will not continue to do so. This history must be considered and accounted for in terms of the likelihood of future occupation of Mesita del Buey in the Area G RRA Model. The wide range of possible human exposure scenarios ranges from the excavation of basements, kivas, impoundments, or other belowground structures to the siting of farms and entire communities and their associated infrastructure. In addition to estimating exposures to individuals, we are interested in a population dose or risk assessment with the goal of keeping the cumulative doses to all individuals ALARA, as required by DOE O 458.1. That probabilistic population dose assessment is the appropriate risk metric to be used in the decision analysis for the disposition of the 33 Shafts.

With the identification of this critical modeling endpoint, we can determine the model structure required to provide the calculation. The human receptors to be considered for the RRA are identified in the FEPS analysis [27] (again, where the “S” in “FEPS” is for exposure scenarios) and CSM [28]. The dose calculation depends on several basic factors: The first of these is the way in which human receptors interact with their environment, which determines exposure pathways. For example, a farmer would receive exposures via external irradiation from contaminated soil, and internal irradiation from inhalation of dust and gases, ingestion of produce, ingestion of livestock fed contaminated fodder, and inadvertent ingestion of soil while working the field. Depending on the occupancy situation and source of water, the farmer might also receive dose via inhalation of indoor air and ingestion of contaminated water. Each of these also involves a rate of inhalation or ingestion. That is, at what rate are produce, animal products, water, and soil consumed? For external exposure pathways, the amount of time that a receptor spends engaged in each of these activities is a driving set of parameters. In the farmer example, this is broken down into the fraction of time spent in the field, indoors, or elsewhere. This is also multiplied by the duration of the farmer’s activities, as in the number of years spent farming at a contaminated location. The last parameter set in determining dose is the concentration of contaminants in the exposure media itself. For the suite of modeled radionuclides, what is the concentration of each in soils, water, and air to which people are exposed? Each of these factors is multiplied together to define exposure rates. These exposure rates are then multiplied by dose conversion factors (DCFs) to arrive at a dose from each contributing radionuclide (and its short-lived progeny), and is summed to arrive at a dose. This is calculated using standard dose assessment algebra [29, 30], but it must be noted that each of these inputs contains a degree of uncertainty, requiring that each be defined probabilistically so that their influence on the resulting dose uncertainty can be determined. Many practitioners fail to take the important step of defining these inputs probabilistically, and so are left with no way to evaluate their significance in the resulting uncertainty inherent in the calculation of dose.

The wastes at Area G are also prone to an exposure mechanism shared by those at several other LLW sites, and indeed most hazardous waste landfills, municipal landfills, and mining tailings piles: long-term and unmitigated erosion will expose the waste, which could result in direct exposures of humans to the wastes themselves. This may or may not be an action-driving exposure scenario, depending on the nature of the wastes at the time of exposure. Most radioactive wastes will have decayed to lesser activities, and waste forms may have degraded from discrete objects to less recognizable forms, by the time they are exposed. Exposure scenarios could range from a person picking up an interesting-looking object to simply traversing contaminated soils. These scenarios must be assessed, and their severity will depend on the amount of time before the waste is exposed thorough natural processes, as well as receptor activities at the time.

Given these methodologies for dose assessment, the RRA must determine the radionuclide concentrations in the exposure media of interest. This calculation is generally complex and computationally intensive, as it involves contaminant transport through many interacting media, by many physical, chemical, and biological, and even nuclear processes. The FEPS analysis [27] and CSM [28] for the RRA guide model design for contaminant transport. The most obvious starting point for any contaminant transport calculation is the source of the contamination. In the case of the Area G RRA, this is the disposed radioactive wastes in pits, trenches, and shafts on Mesita del Buey, and the retrievably stored RH TRU in the 33 Shafts. The role of the contaminant transport calculations is to determine how the radionuclides present in these waste forms migrate to exposure media at the various points of exposure to humans. The FEPS and CSM identify potential mechanisms for contaminant transport, including

- dissolution, or leaching, from the waste forms into water that comes into contact with them,
- advection, dispersion, and diffusion of soluble radionuclides in groundwater,
- diffusion of volatile radionuclides in interstitial air and into the atmosphere,
- partitioning of radionuclides between water, air, and various solid media (e.g. waste forms, soils, rocks, concrete),
- resuspension of contaminated particles from the ground surface into the atmosphere,
- regional dispersion in the atmosphere,
- surface water and sediment transport into local watercourses and thence into larger rivers,
- uptake of radionuclides into plant roots that intrude into wastes, and redistribution within plant tissues,
- bulk material translocation by burrowing animals,
- bulk material translocation through erosion, and of course
- transition from one radionuclide to another through radioactive decay and ingrowth.

These processes apply to many near-surface radioactive waste disposal sites. Each process is complex and the subject of extensive research in its own right, and yet each must be reduced to a reasonably simple mathematical model in order to make calculations tenable. Most of these process-specific models take the form of differential equations, all of which are coupled and must be solved simultaneously. Through consultation with subject matter experts, a collection of equations and systems is developed so that the fundamental effects of each process are captured. At this stage of model development, the intent is not precision, but rather inclusiveness. It is more important to be sure to include all relevant features, events, processes, and exposure scenarios, than to make sure that each one accurately mimics natural behavior. These are parameterized with stochastic model inputs that may have substantial uncertainties. The goal at this point is to assure that the true behavior of the system and of each contributing model is captured within those uncertainties. Selective model refinement follows later, once the entire risk assessment model is running.

With the fundamental FEPS identified, model development takes two parallel paths: Model structure is implemented by programmers, who assemble and link the equations of contaminant transport and receptor exposures. Simple placeholder values are used for model inputs, so that the model may be run and tested. Stochastic parameterization is developed by subject matter experts and statisticians. As robust and defensible stochastic model inputs are developed, they are included in the model, replacing the programmer’s placeholders.

Quality assurance procedures are applied throughout this process. Programmers cross-check each other’s work, assuring that the correct equations are being solved, and that they are being solved correctly. The stochastic input parameter development process is also extensively checked, so that each value pulled from a dataset or from the literature is done accurately, and that the statisticians’ input distribution derivations are performed correctly. Although the quality assurance process can be tedious and laborious, often doubling the overall cost of a project, its value cannot be overstated. If an analysis is based on faulty information, introduced by inattention or errors in transcription, it will produce incorrect results. Obviously, this does not support defensible decision making.

The current state of development of the Area G RRA model is this parallel development of model structure and stochastic model input development. Following completion of the initial Area G RRA Model, development enters the iterative phase. The initial model, with its relatively broad uncertainty, is subjected to a sensitivity analysis, resulting in the identification of those input parameters whose uncertainty contributes most to the uncertainty in the model endpoints.

Each of the most important input parameters is examined using value-of-information techniques to determine the benefit of reducing its uncertainty. If decision makers are satisfied that they can make a defensible decision with the model and its uncertain results, then no further work need be done. If, on the other hand, a decision maker feels that the uncertainties are too great, the sensitivity analysis identifies how global uncertainty can be reduced by addressing uncertainty in specific model inputs. In this case, the important probabilistic input distributions are further studied, and their uncertainty is reduced. When the model is updated and rerun, the uncertainty in results of interest (e.g. population doses) will also be reduced, and the decision maker can decide if the reduction is sufficient to make a decision. This process is repeated until the decision maker is satisfied. A future decision analysis, in which a broader range of risks and costs will be assessed, will assist in this respect.

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