A Preliminary Radiological Risk Assessment Model for Disposition of Remote-Handled Transuranic Wastes at Los Alamos National Laboratory Area G – 20116

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ABSTRACT

The U.S. Department of Energy (DOE) operates 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. 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 volcanic 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 host to LANL, Area G, and the townsites of Los Alamos and White Rock, with residences as close as 1400 m from Area G. These 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 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 necessarily 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 future access to 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 FEPSs 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 presents the initial draft of a defensible, transparent, and reasonably realistic model, which is based on the state of knowledge of the wastes, the site, and the FEPSs that govern contaminant transport from wastes into the environment and subsequent exposures to humans and other biota. Probabilistic model input distributions represent uncertainties inherent in the real and modeled systems. The results of the Area G RRA Model inform decisions regarding the disposition of the RH TRU in the 33 Shafts.

INTRODUCTION

Los Alamos National Laboratory (LANL) has disposed radioactive wastes at Material Disposal Area (MDA) G since the late 1950s. The Laboratory is owned by the United States Department of Energy (DOE), which is ultimately and perpetually responsible for the disposed wastes. While the bulk of the disposed materials at Area G are low-level radioactive waste (LLW), other types of radioactive wastes, including those containing significant concentrations of transuranic radionuclides, are disposed or stored at the site.

Area G is located in Technical Area (TA) 54 on LANL property, in northern New Mexico, identified in Fig. 1. The facility shares a border with the Pueblo de San Ildefonso to the north, and is about 1400 m from the nearest residence in the town of White Rock, to the east.

Among the radioactive wastes stored (not disposed) at Area G is remote-handled (RH) transuranic waste (TRU) in 33 Shafts. These are designated as RH since they are so radioactive that they may not be safely handled directly, with dose rates of up to 12,000 mSv/hr (1,200,000 mrem/hr) [1, 2], or 105,000,000 mSv/yr (10,500,000,000 mrem/yr). By comparison, the allowable future effective dose equivalent (EDE) for members of the public is 0.25 mSv accrued in a yr (25 mrem in a yr).

These wastes were intended to have been retrievably stored in Shafts 200–232 [3]. Exhumation and treatment of these wastes would involve careful consideration of potential worker exposures, potential risk to the public, and expense. Leaving them in place would require an analysis to assess compliance with the U.S. Environmental Protection Agency's Title 40 of the Code of Federal Regulations (CFR) Part 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes* [4, 5] and approval by the Administrator of the EPA. This situation has prompted DOE to conduct a decision analysis regarding the disposition of the RH TRU wastes in the 33 Shafts. The decision analysis requires the development of a formal assessment of the human health and environmental effects resulting from various decision alternatives, which is accomplished by this Area G Radiological Risk Assessment (RRA).

The definition of TRU is waste that contains alpha-emitting radionuclides of atomic number greater than 92 and half-lives greater than 20 years in concentrations greater than 3700 Bq (100 nCi) per gram of waste (DOE 1982), although it may contain other radionuclides as well. All of the wastes in the 33 Shafts meet these criteria. Following the issuance of *Immediate Action Directive 0511-21* [6], TRU has generally not been allowed to be disposed in the near surface, although there are exceptions[7, 8].

As transuranic waste, the RH TRU has not been previously evaluated in the LANL Area G Performance Assessment (PA) (French et al. 2008), since these analyses, responsive to DOE Order 435.1 *Radioactive Waste Management* [9], consider only LLW. Neither have these wastes been previously evaluated in the LANL Area G Composite Analysis (CA), also prescribed under DOE O 435.1, nor in the Site-Wide Environmental Impact Statement (SWEIS), since it had been asserted that the 33 Shafts would be removed from Area G, and their contents would be treated and disposed elsewhere (ostensibly at the Waste Isolation Pilot Plant, or WIPP), in accordance with the Order.

Given that the wastes in the 33 Shafts are TRU, a disposal action would trigger an analysis under EPA's 40 CFR 191 [4, 5], as referenced in DOE O 435.1 [9]. Another applicable DOE Order governing management of these unique wastes at Area G is DOE O 458.1 *Radiation Protection of the Public and the Environment* [10]. While the time frame for compliance is 1000 yr in DOE O 435.1 and 10,000 yr in 40 CFR 191, there is no upper limit on compliance times mentioned in DOE O 458.1. This RRA likewise does not have an upper limit to the time of compliance, and the RRA Model may be run by the user for any length of time, although it is expected that the entirety of Mesita del Buey will be eroded and any remaining wastes will be exposed within 100,000 yr or so [11].

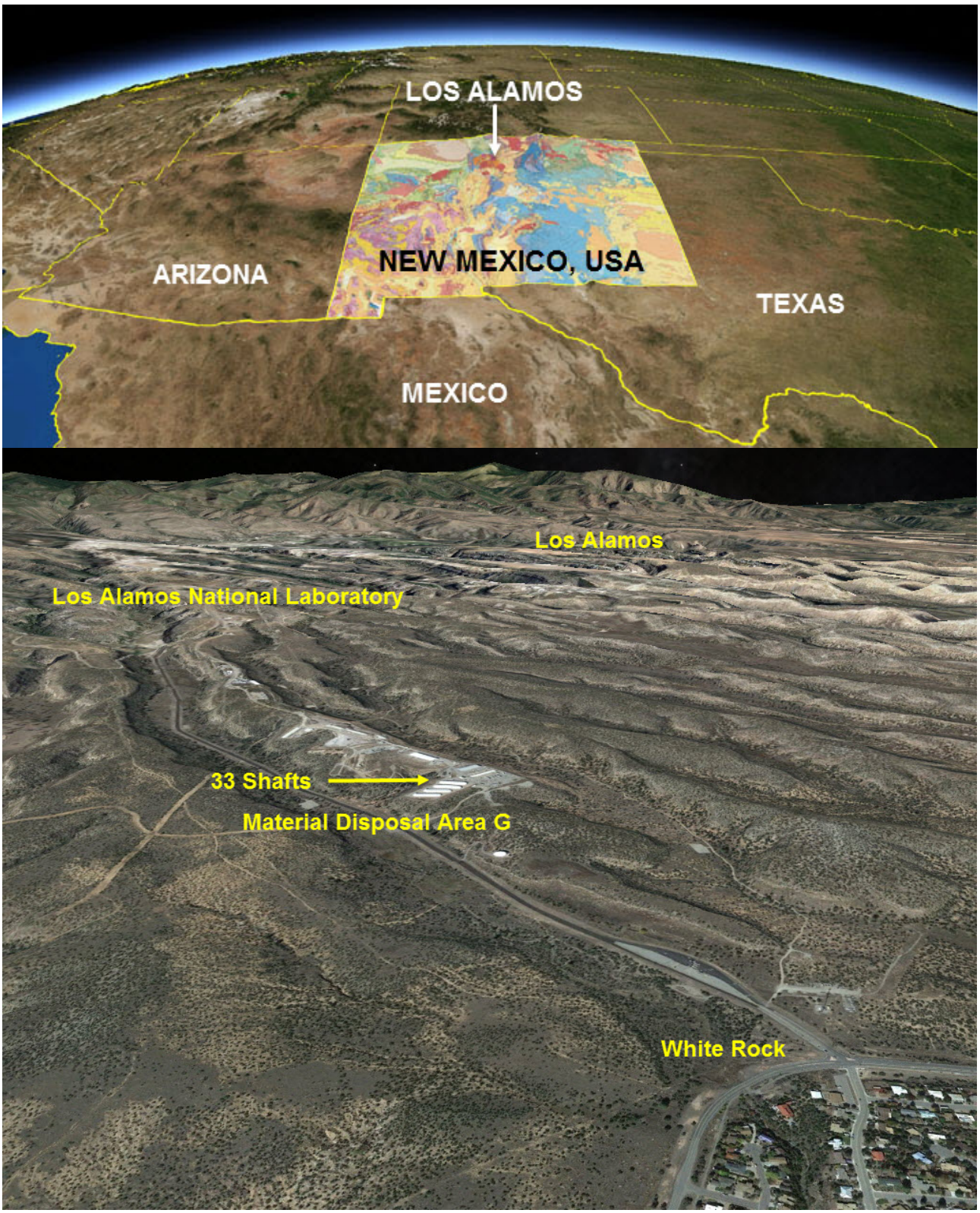

Fig. 1. Location maps for Area G and the 33 Shafts

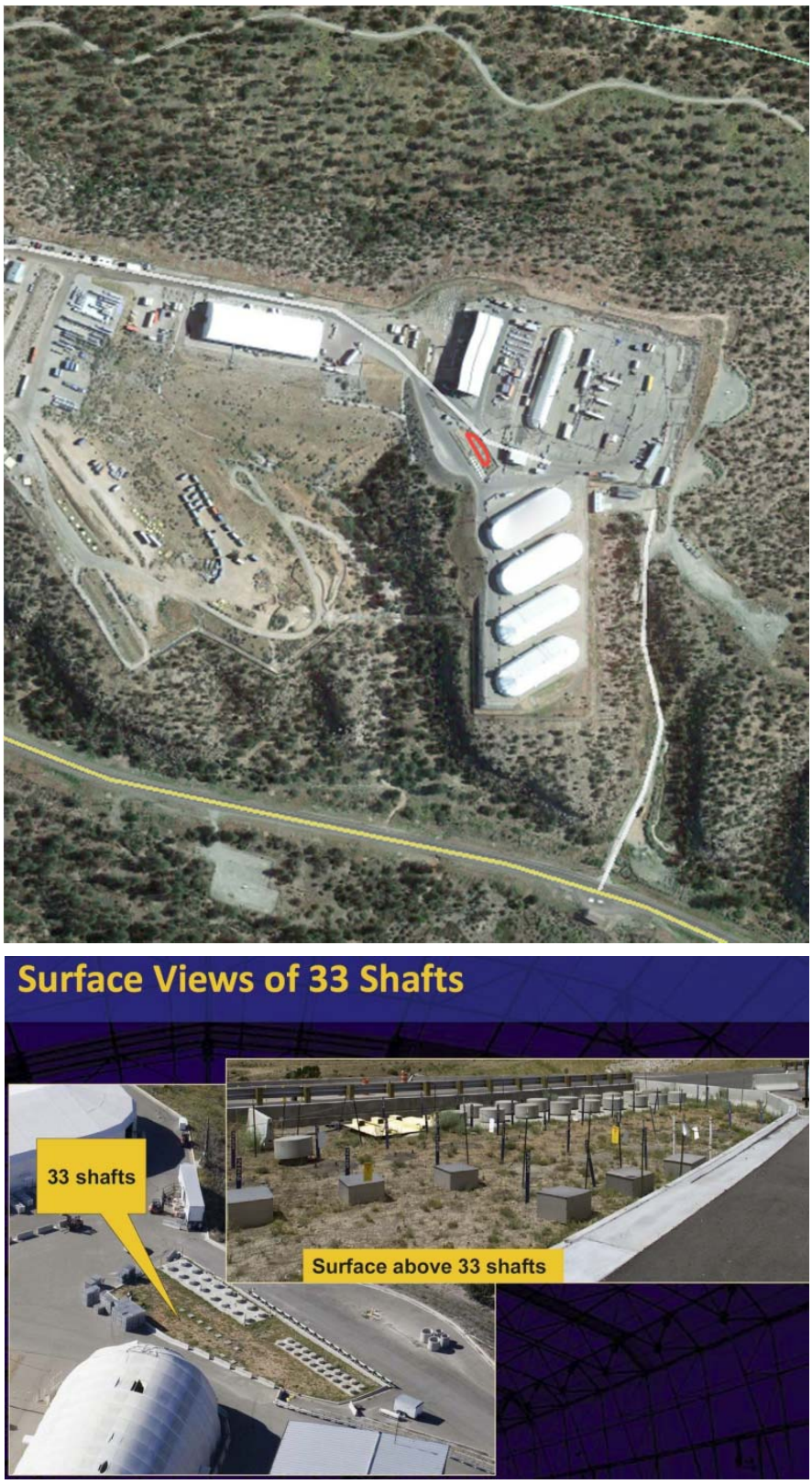

Fig. 2. View of the 33 RH TRU Shafts in Area G [1].

Irrespective of the particular regulation that is considered applicable to the problem, the essential risk analysis is the same. The calculations of contaminant transport through engineered and natural materials and the subsequent assessment of risks to human health and the environment are the same for all such risk assessments. The Area G RRA Model is designed in such a way that it can be responsive to a variety of assessment endpoints, and compliance with various regulations can be evaluated. In this sense the RRA is generic in its calculations, free from the constraints that would be imposed by strict adherence to the standard definitions of PA offered by DOE O 435.1 or 40 CFR 191. This allows for a more comprehensive and rigorous evaluation of risks, and therefore a broader basis for decision making for the disposition of the RH TRU wastes. The goal of the RRA is to provide a realistic analysis that is designed to inform decisions about the disposition of wastes and closure of the site. These decisions invoke the concept of optimizing risk reduction and cost.

The Area G RRA is different from similar investigations, such as the PA and CA required by DOE Order 435.1. While the LANL PA/CA [12] is intended to demonstrate compliance, it is not particularly focused on decision making beyond what is necessary to comply with the Order. The PA/CA also is subject to a number of regulatory constraints and performance criteria, such as a limited amount of time specified as the period of performance (1000 yr), the exclusion of specific dose pathways (e.g. radon and its progeny in air), and the specification of compliance locations that are an arbitrary distance from the waste site boundary (100 m). In contrast, the RRA evaluates potential future risks to human health and the environment, with no restrictions on where or when they might occur. Such a risk assessment is more in line with the analyses recommended in both EPA 40 CFR 191 and DOE O 458.1. There are no prescribed receptor types or behaviors—the goal is to provide a realistic analysis that is based on the best information available, designed to inform decisions about the disposition of wastes.

In addition to informing decisions about the RH TRU shafts, the Area G RRA Model is capable of running analyses to evaluate the performance objectives of EPA's 40 CFR 191, and is responsive to DOE Orders 458.1 and 435.1, including endpoints of population dose assessment, and ecological risk assessment, and the goal of keeping doses and risks as low as reasonably achievable (ALARA), considering all wastes disposed at the site. Indeed, as part of the CA required by DOE O 435.1, all radioactive materials expected to remain at LANL are included. The model is transparent and accessible to all stakeholders, and is developed with their concerns in mind, so that they may understand how it informs decisions about radioactive waste at Area G that affect them.

PURPOSE

The Area G RRA Model is a tool to aid in the assessment of possible future effects of disposed radioactive waste on the health of humans and the environment, as described in the *Conceptual Site Model for the Area G Radiological Risk Assessment* [13]. This is motivated by EPA radioactive waste regulations and internal DOE Orders that require such an assessment in order to determine whether there is a reasonable expectation that specific performance objectives will be met. These performance objectives are generally of the form that a specified dose, risk, contaminant concentration, or contaminant flux not be exceeded within a given time frame. For example, DOE Manual 435.1 1 IV.P.(1)(a) limits the effective dose equivalent (EDE) from wastes disposed after 26 Sep 1988 (the effective date of the original Order) to "representative members of the public" to 0.25 millisieverts (mSv) or 25 millirem (mrem) in a year, within a compliance period of 1,000 yr following closure of the site [14]. Subsection (c) limits the area-averaged flux of all radon isotopes emanating from the ground to 0.74 becquerels per square meter per second ($Bq/m^2 \cdot s$, or 20 picocuries per square meter per second, $pCi/m^2 \cdot s$) within the first 1,000 yr. Specific values and time frames of performance objectives differ between regulations, but all are explicitly or implicitly probabilistic, and all require the development and modeling of the most significant contaminant transport and human and ecological exposure processes. The development of significant processes is documented in the *Analysis of Features, Events, Processes, and Exposure Scenarios* [FEPSs] *for the Area G Radiological Risk Assessment* [15].

Common to all these performance metrics is the same underlying model of the transport of contaminants in the environment. This includes the release of radionuclides from waste forms into the surrounding environment by leaching into water, volatilizing into air, being transported by plants and animals, and being eroded along with the rest of Mesita del Buey. The model tracks the migration of these contaminants through the environment to locations and within environmental media (air, water, soils) to which plants and animals (humans, in particular) could be exposed. As humans and other species interact with these exposure media, they incur radiological doses or other health risks. These risks are quantified in the RRA Model, and are compared to appropriate performance objectives. This information is provided to decision makers about paths forward for the 33 Shafts, which could include site closure, investigations into specific remedial alternatives, or additional information gathering.

Demonstration of compliance with the various performance objectives is also intended to be probabilistic, either explicitly or implicitly. The Containment Requirements of EPA's 40 CFR 191.13, for example, demand the construction of a complementary cumulative distribution function (CCDF) that shows the results of a very specific probabilistic analysis. The aforementioned DOE M 435.1 1, however, implies a probabilistic assessment by using the words "reasonable expectation" in referring to meeting specific objectives. Probabilistic analysis also provides decision makers with essential context regarding the uncertainty of their decisions. For these reasons, the Area G RRA Model must be probabilistic, meaning that nearly all model inputs are stochastic, reflecting the state of knowledge about each value, and that the model is run many thousands of times in order to explore the uncertainty imposed by our inherently limited state of knowledge.

The purpose of the Area G RRA Model, then, is to generate site-specific results that, while incorporating inherent uncertainties, can be compared with specific performance objectives that are required by DOE and EPA. Sensitivity analysis of RRA Model results further provides information about which transport and exposure processes are the most important, giving insight that is useful in mitigating risks and doses and in maintaining and monitoring of the site.

The Area G RRA Model, shown in a screen capture in Fig. 3, is developed with the user in mind, using the system analysis model-building software called GoldSim (www.goldsim.com), which was developed for this purpose in support of the Yucca Mountain Total System Performance Assessment. Models developed using this platform can be enhanced with extensive explanations and illustrations of modeling concepts and processes, and can offer the user a certain degree of control over the analysis, in order to explore the effects of different options, such as the choice of closure cover. While the model development version, GoldSim Pro, is proprietary commercially-developed software, the RRA Model is available to run with the free GoldSim Player. The Player version allows the user to examine the Model in the finest degree of detail, and to exercise options provided through various Control Panels.

THE AREA G SITE AND THE 33 SHAFTS

Area G is host to dozens of waste disposal pits and hundreds of shafts cut into the Bandelier Tuff Unit 2, which forms the top of Mesita del Buey (see Fig. 4). This flat mesa is bordered to the north by Cañada del Buey and land owned by the Pueblo de San Ildefonso. To the south is Pajarito Canyon, which is deeper and has a more pronounced and active cliff edge than that to the north. Waste pits and shafts, many of which are over 10 m deep, are located sufficiently far from these cliff edges so that waste is not expected to be exposed within 1000 years following site closure [11], the compliance time specified in DOE O 435.1 [9]. There is a possibility, however, that some wastes could be exposed within 10,000 years, the compliance time specified in 40 CFR 191 [5].

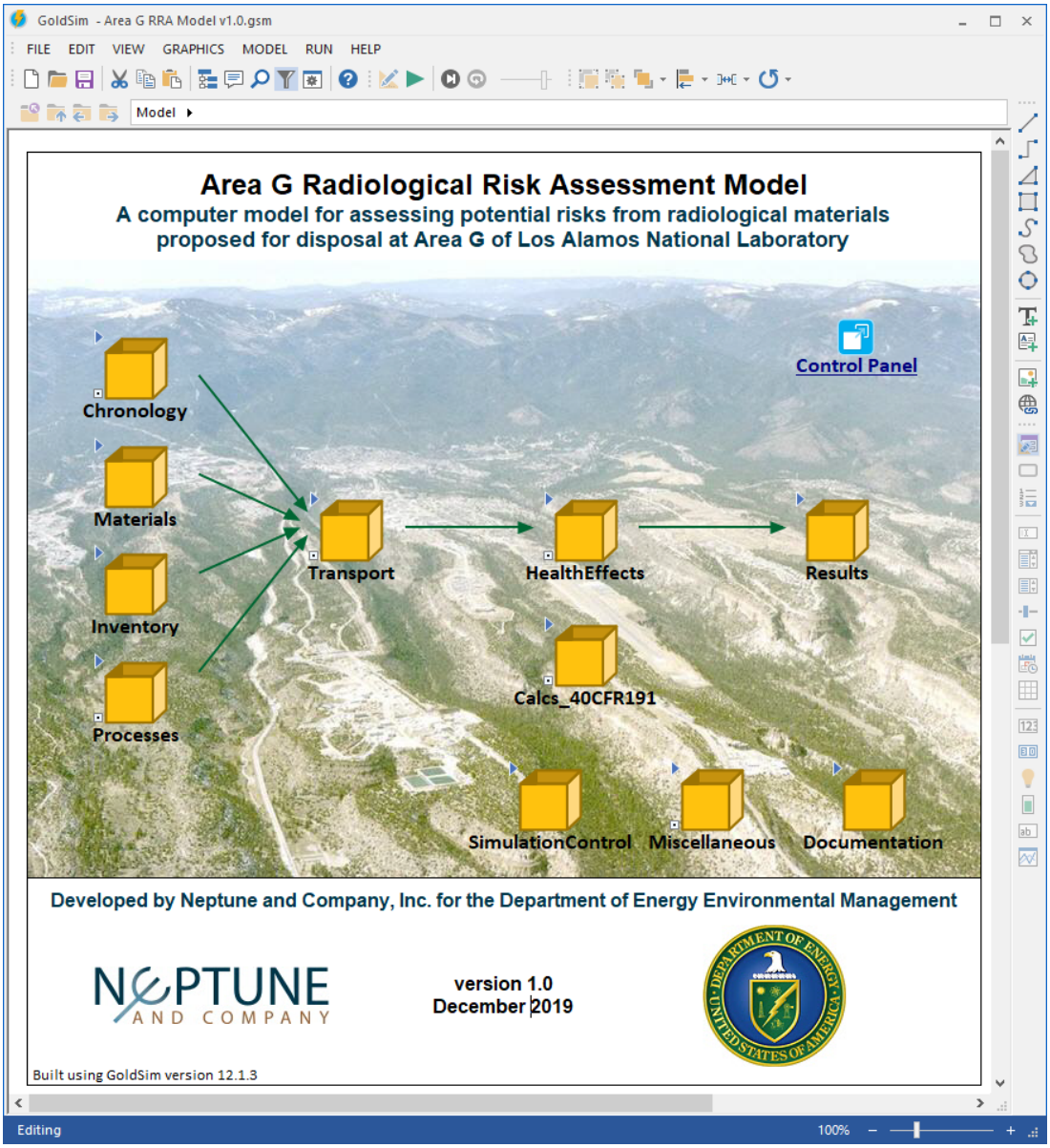

Fig. 3. Top level of the Area G RRA Model, showing model organization

Radioactive Waste Disposal at Area G

The bulk of disposed radioactive waste at Area G is LLW, by volume. Starting with the first disposals in 1957, and until the issuance of *Immediate Action Directive 0511-21* of 1970 [6], all types of radioactive wastes were disposed in the early pits, including what is now defined as LLW and TRU. Following the IAD, TRU wastes were stored in a retrievable configuration above and below ground. Removal actions for most of that TRU are ongoing, and that waste slated for disposal at WIPP is not considered in PAs or CAs for the Site. The first version of the DOE Order *Radioactive Waste Management* came into effect on 26 September 1988, and it specifically ignored waste disposed before that date. Waste disposed after that date is subjected to PA. In 1994, however, the Defense Nuclear Facilities Safety Board recognized that wastes disposed earlier were not being considered in risk assessments, and issued *Recommendation 94-2* [16], compelling DOE to develop the CA concept, wherein all radioactive materials left at the site are to be considered in the modeling. TRU waste disposal was and is still prohibited under the 1970 IAD.

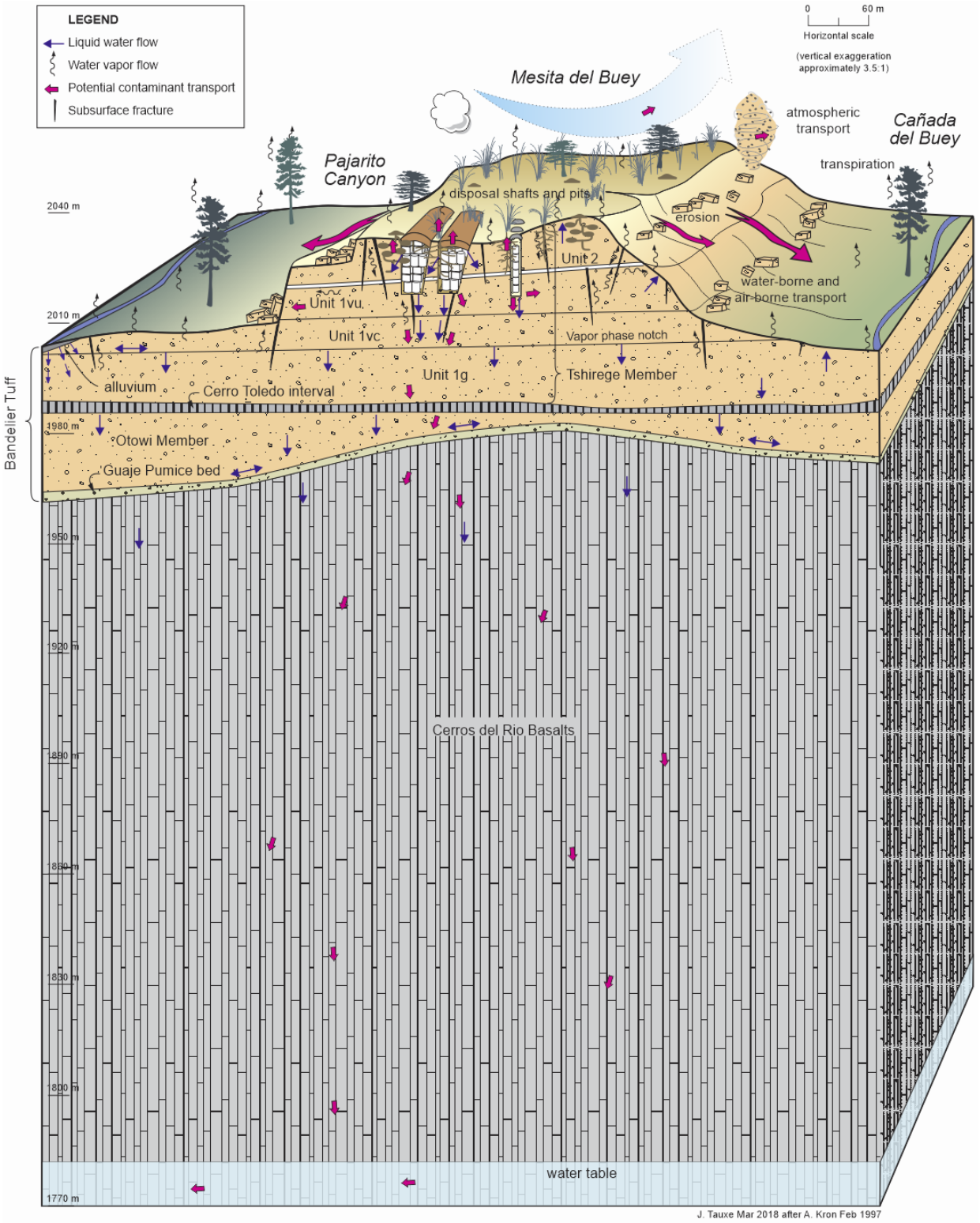

Fig. 4. Geologic and environmental conceptual of Area G

The RH TRU in the 33 Shafts was emplaced in the mid-1980s, in what was intended to be a retrievable configuration, since no permanent disposal path for TRU existed at the time. This timing happened to overlap with the issuing, remanding, and re-issuing of 40 CFR 191, EPA's standard for disposal of TRU [4, 5]. The proposed *in-situ* disposal of TRU in the 33 Shafts is to be evaluated under the later and more stringent 1993 version of that regulation.

Recognizing the long-term liabilities of DOE's radioactive wastes [17], disposals of radioactive waste at MDA G have been curtailed, reserving the remaining space for only particularly problematic wastes that still have no path forward off the site.

Waste Characterization for the 33 RH TRU Shafts

Three basic physical configurations were used for the 33 Shafts (see Fig. 5). All are vertical shafts augured into the Bandelier tuff. Configuration B is unique for the disposal of an experimental nuclear reactor, enclosed in a steel pipe. The other shaft types consist of an outer shell of corrugated steel pipe (CSP) and an inner steel casing. In Configuration A, the annulus between the CSP and the casing contains concrete. A variety of plastic and metal cans were used to transfer the wastes from hot cells to the shafts, but the physical integrity of these cans is in doubt. The top of the wastes are estimated to be less than a meter from the ground surface.

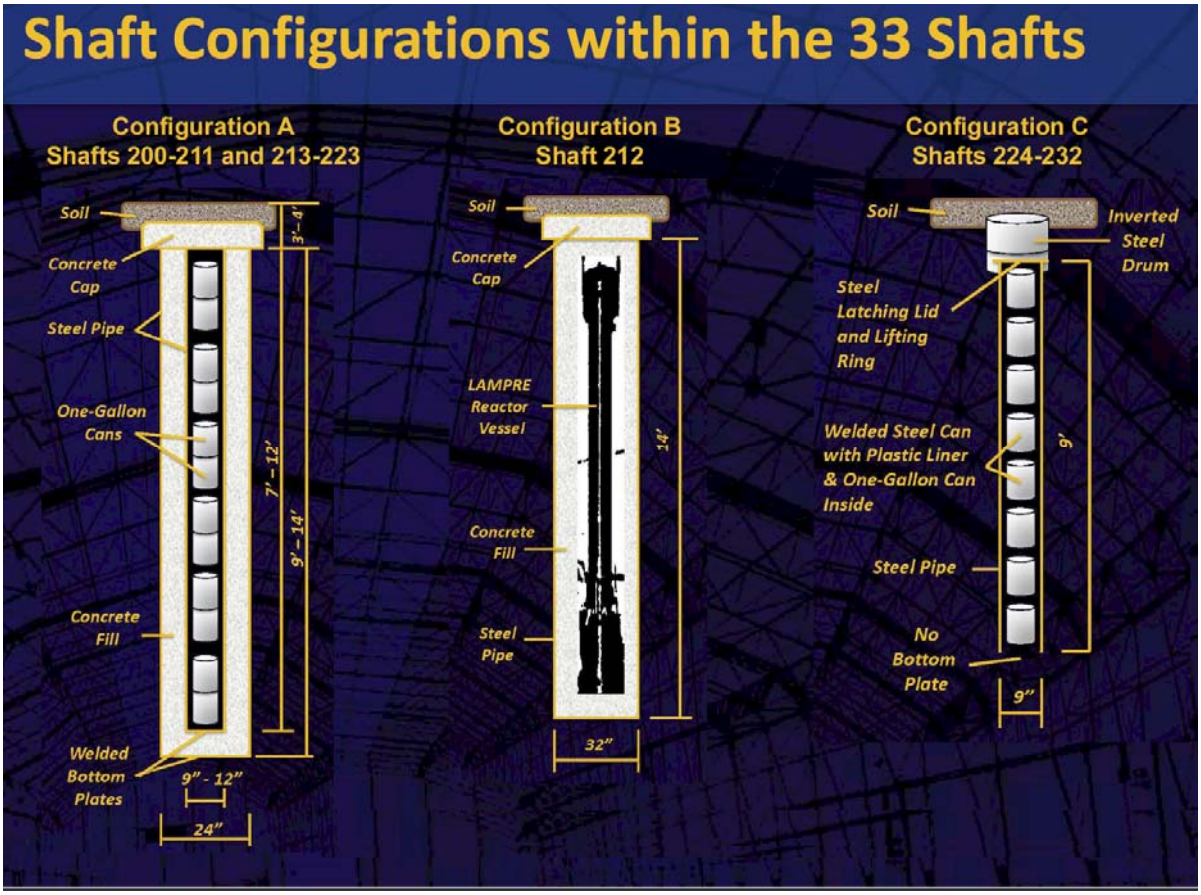

Fig. 5. General configurations of the 33 RH TRU Shafts in Area G [1].

The contents of the 33 Shafts is characterized by LANL [2] as such:

> The waste in the 33 shafts was generated in hot cell operations at the Chemistry and Metallurgy Research (CMR) facility, except for shaft 212 which contains the reactor vessel from a small research reactor called the Los Alamos Molten Plutonium Reactor Experiment (LAMPRE).

> CMR waste was generated from examination of irradiated fuels from the Liquid Metal Fast Breeder Reactor and other advanced-fuel evaluation efforts, including the ROVER space propulsion program. A single waste package in shaft 232 suggests that materials from Three Mile Island also may have been examined. Generator records indicate the waste includes residual samples, spent equipment and waste materials typical of hot cell operations.
>
> An extensive review of historical documents in 2005 included waste generator records that described the waste and quantity of Pu-239, U-235, and mixed fission products [MFPs]. Other data sources also were examined. The content and accuracy of the data are typical for legacy waste generated from 1979-1987.

The estimated total volume of radioactive waste in the 33 Shafts is 3.39 m^3, with a mass of over 15 Mg (metric tonnes) and an estimated total activity of over 142 TBq (3847 Ci) at the time of emplacement [2]. Contact doses were estimated at up to 12 Sv/hr (1,200,000 mrem/hr, or 10,500,000,000 mrem/yr), though these activities and dose rates have dropped due to radioactive decay, and will continue to do so.

However, except for Shaft 212 (LAMPRE reactor) and two other shafts, the documented inventory of 30 of the 33 shafts is limited to Pu-239, U-235, and MFPs [2, 18, 19]. This implies that other radionuclides must exist (e.g. at a minimum, the presence of U-235 implies a presence of other uranium isotopes, notably U-238, and their progeny), so additional characterization work would ostensibly be performed before making a decision to dispose the shaft wastes *in-situ* , elsewhere in Area G, or off-site.

THE DECISION PROBLEM

With the Waste Isolation Pilot Plant (WIPP), a path forward for TRU now exists, and other TRU at Area G is gradually being removed to WIPP. Retrieval of the RH TRU Shafts, however, presents significant risks to workers, and significant costs to the taxpayer. These challenges prompted this RRA.

A prototype decision model was constructed to address the problem of disposition of the RH TRU by Neptune, using GoldSim, for Predicus. This was presented at the Waste Management Symposia 2010 [20]. The essential decision logic implemented in that model is shown in Fig. 6, with the current decision point highlighted.

DOE has decided to effect the on-site disposal path first, rather than to initiate removal of the TRU wastes. As of this writing, the evaluation of compliance with 40 CFR 191 is being evaluated. Remedial alternatives are being developed in an attempt to achieve compliance, especially with the Containment Requirements of the regulation, §191.13. A release is defined as radionuclides being transported from the waste to the accessible environment, which is defined in the regulation. Section 191.13 requires that releases to the accessible environment be a small fraction of the disposed inventory, for 10,000 years following the disposal action, as outlined in Appendix A of 191.

MODELED PROCESSES

Following a thorough analysis of site-specific features, events, processes, and exposure scenarios (FEPSs) [15] and subsequent development of a conceptual site model (CSM) [13], the following contaminant transport processes are included in the Area G RRA Model.

On-site transport processes

One of the most ubiquitous contaminant transport processes in PA modeling is in moving groundwater, including the unsaturated and saturated zones. The intense focus on hydrogeological processes, often to the exclusion of other potentially significant contaminant transport mechanisms, is due in part to the history of the field, which was developed largely by hydrogeologists and groundwater engineers. In the humid sites like those in the eastern US, groundwater commonly is the most significant process, but in dry sites in the west, like Los Alamos, groundwater becomes an issue only in systems that have been

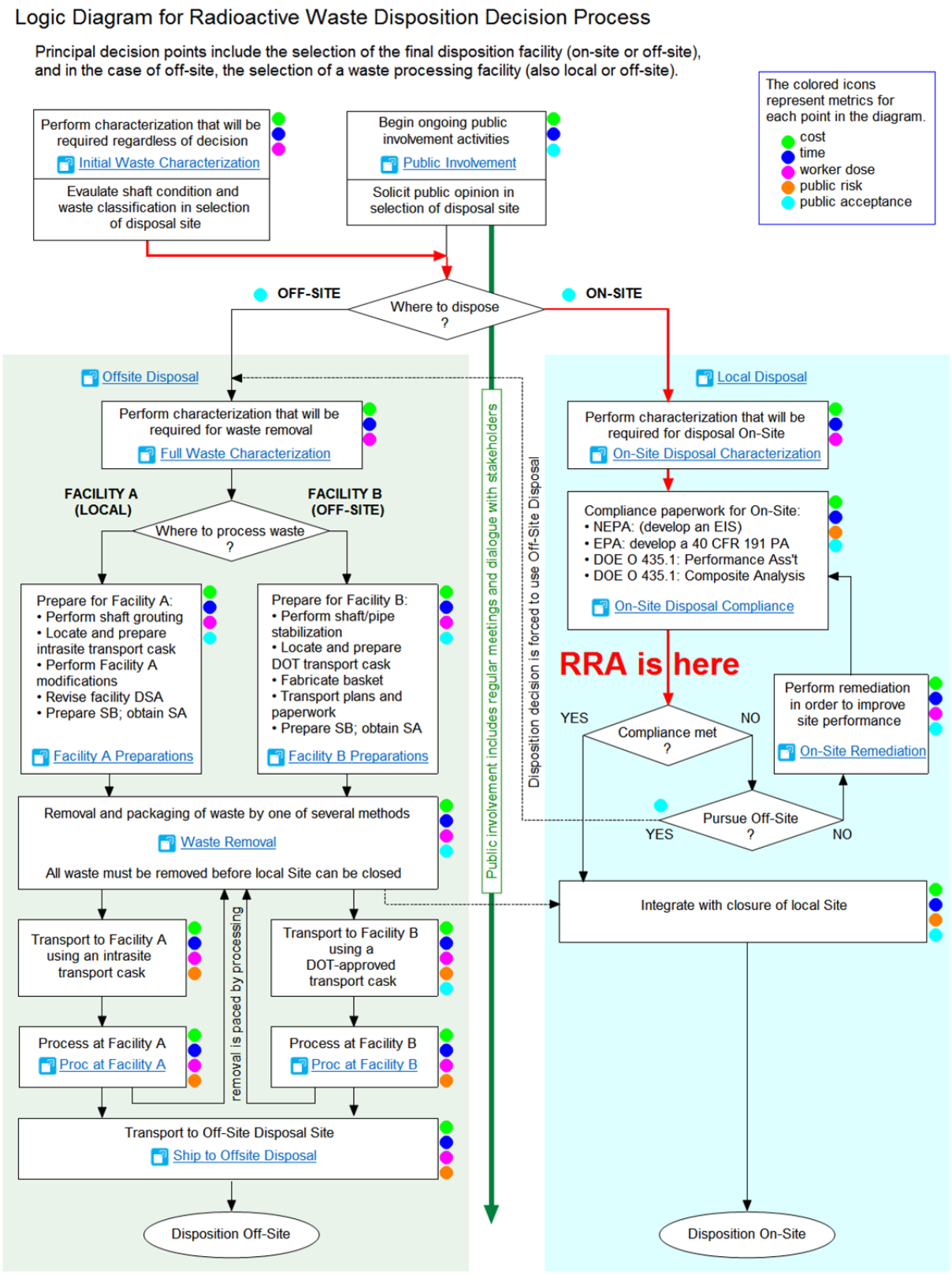

Fig. 6. Decision logic diagram showing the current focus of the RRA for the RH TRU Shafts at Area G

disturbed by human actions, such as application of large amounts of water to disposal units, for a variety of reasons.

In areas that have not received unnatural amounts of water applied at the surface, infiltration and unsaturated zone to the water table (at a depth of about 350 m below Mesita del Buey) are extremely slow processes, with vertical Darcy velocities less than 1 cm/yr [21]. Under natural conditions, then, contamination would not reach the water table for thousands of years.

The saturated zone below Mesita del Buey moves relatively quickly in thick fractured basalt [22], with Darcy velocities of over 3 m/y. This provides significant dilution to contaminated recharge, and also moves the contaminants quickly beyond the controlled area defined in 40 CFR 191 [5]. Groundwater resources are to be protected under 191 as well, with contaminant concentrations anywhere in groundwater being compared to EPA's Maximum Concentration Limits (MCLs), as defined in 40 CFR 141.66 [23].

Each waste disposal region (WDR) can be modeled individually with respect to groundwater, thanks to the principle of superposition of plumes, wherein overlapping plumes do not affect each other as long as solubility limits are not reached [22, 24-26]. Since the lateral movement of groundwater in the saturated zone is relatively rapid, releases to the water table are considered releases to the accessible environment as a convenience of calculation, since while there is dilution, there is no appreciable permanent sink for contaminants within the controlled area.

A more significant contaminant transport mechanism, often overlooked or prematurely dismissed in PA work, is that of biotically-induced transport, including plants and animals [27]. Burrowing animals, including primarily ants and small mammals, have been found to move appreciable amounts of materials from the subsurface to the surface. The work of ants alone is the most significant transport mechanism at LLW disposal sites like those at the National Nuclear Security Site (NNSS, formerly the Nevada Test Site), where ant nests have been found to extend to depths over 4 m from the ground surface [28, 29]. Burrowing mammals and ants as contaminant transporters are modeled as moving bulk materials from various burrow depths to the ground surface, as seen in gopher mounds.

Plants bring subsurface contamination to the surface by a different mechanism. They are selective in their absorption of chemicals by roots, and different chemicals are routed to different parts of the plant. This chemically and physiologically selective uptake of contaminants is captured in plant/soil concentration ratios (CRs), which are catalogued for various plants and chemicals [27, 30]. The research is incomplete, however, and commonly focuses on crop plants. The RRA Model adopts generalized CRs and applies them to native plants and produce grown by a resident farmer. The transport calculations can be summarized as adsorption at the roots from surrounding soils using the CRs, followed by translocation of contaminants to the aboveground plant parts, which senesce or ultimately die off, giving up the contamination to the surface soils [27]. Here they are combined with animal burrow spoils, enriching the surface soils with contaminants. All such biotically-induced contaminant transport constitutes a release to the accessible environment.

A further local transport mechanism is diffusion of volatile contaminants in subsurface air. Modeled volatile constituents include H-3, C-14 as CO_2 and CH_4, Kr-85, I-129, and Rn-222. The diffusion of these constituents in pore air is modeled within the RRA Model, using a corrected application of GoldSim's native modeling tools [31]. In general, diffusion is upward from concentrations at depth to the atmosphere, which acts as a sink. Radon-222, in particular, is tricky to model, since it has a half-life of less than 4 days, and yet it leaves a trail of progeny as it diffuses through the subsurface—notably Pb-210 and Po-210. It is important for modelers to not neglect the effects of radon progeny as they build up in near-surface soils, since they can significantly contribute to dose to a person in a dwelling or on the ground surface [28].

Off-site transport processes

This preliminary version of the RRA does not consider off-site doses and risks, given the assumption that for the purposes of decision making about the 33 Shafts, on-site risks to a resident will be controlling. Therefore, the contaminant transport of materials that have left Mesita del Buey (into canyons, groundwater outside the area of interest, or the atmosphere) are not modeled with fidelity. Atmospheric transport of gases and suspended particles is limited to removing contaminants from the mesa to a sink. Similarly, contaminated groundwater is modeled only to about 1 km downgradient of the site, covering the area where mesa residents might conceivably install a water supply well.

Contaminant transport by surface and cliff erosion moves materials into the adjacent canyons, where rudimentary canyon water and sediment transport is performed.

ADVERSE EFFECTS TO HUMANS AND THE ENVIRONMENT

The initial version of the Area G RRA Model evaluates those exposures and health effects to people, wild animals, and plants that are most likely to influence decisions. The initial human health dose and risk assessment assumes that a resident farmer could live on top of any WDR, after the loss of active institutional control. Type of homes and housing density similar to the range of residential neighborhoods in Los Alamos and White Rock. Although readily accessible representative data on property sizes is limited, the range of single-story home and lot sizes from the same source discussed above suggests that an average single-story home size of 186 m2 (2000 ft2) and the 33 Shafts area of 900 m2 (0.2 ac) for a lot size is reasonable [32]. The homesteaders occupying the site before development by the Army in 1942 would have had larger lots and smaller dwellings [33]. The ancient puebloans would have had more small dwellings, but concentrated into villages [34]. Off-site exposures are not evaluated in this preliminary RRA, under the assumption that on-site exposures will be limiting for decision makers. Exposure pathways are typical for resident farmers:

- external exposure from soil (outdoor and indoor in a basement[1]),
- gas inhalation (indoor and outdoor),
- dust inhalation (indoor and outdoor),
- home-produced chicken ingestion,
- home-produced egg ingestion,
- home-produced dairy ingestion,
- home-produced vegetable ingestion,
- home-produced fruit ingestion,
- drinking water ingestion (i.e., from a domestic well), and
- incidental soil and dust ingestion (e.g., via hand-to-mouth transfer)

In addition, since erosion will eventually expose wastes and other contaminated materials at the ground surface, acute exposures to people through contact with these materials is assessed.

The doses and risks to humans are ultimately what informs decisions about cleanup of contamination, as well as costs, worker risks, and other considerations outside the RRA Model. The logic for this decision making is shown in Fig. 6.

Ecological risks are also evaluated for terrestrial and aquatic species. It is uncertain at this time whether these risks will be appreciable compared to human risks, and how they may or may not influence

[1] Basements and kivas are not considered for the 40 CFR 191.15 Individual Protection Requirements, since these specify exposures in the case of "undisturbed performance."

decisions. In order to evaluate this, implementation in the preliminary RRA Model is as a screening assessment of ecological risk.

MODELING CHALLENGES

The most challenging contaminant transport process for modeling at Area G is erosion. There is a complex interplay between downward erosion of cover materials from the surface of the mesa and the erosion at the edge, which is dominated by cliff failure and the formation of large intrusive gullies. The preliminary RRA uses estimates of surface erosion informed by modeling with landscape evolution models such as SIBERIA [11, 35-40]. Such models, however, are poor at capturing the geotechnical problems of cliff failure. The retreat of the mesa edge, which eventually exposes the waste disposal units themselves, is modeled using rates apparent from regional geologic history and the estimation of the ages of overturned blocks using cosmogenic techniques [41]. These rates suggest that intrusion in wastes could happen in a few thousand years, and that some disposal units might be completely eroded within 10,000 yr.

Disposal records are commonly quite poor at radioactive waste disposal sites. One reason for this is the general attitude about waste, which is that once it is disposed, it can be forgotten about. The goals of the generator are two-fold: get the waste removed from the workplace to the disposal site, and make sure that workers are safe in doing so. This results in deliberate over-reporting of package inventories to be on the side of caution for worker safety, and the omission of radionuclides that are not important to worker safety. The reported inventories for the 33 Shafts are a case in point: For 30 of the 33 shafts, the only materials reported are Pu-239, U-235, and mixed fission products (MFPs). The first two are fissionable, with more strict accounting than most radionuclides, and the MFPs are, collectively, a worker hazard. Other radionuclides theoretically must be present (e.g. U-238 and other U isotopes, implied by the presence of U-235), but information as to their amounts is lacking. This information gap will present issues for waste characterization for the 33 Shafts.

CONCLUSIONS

The Area G RRA Model provides decision makers in the U.S. Department of Energy with a useful tool for assessing long-term doses and risks to humans and the environment. As an open and transparent model that can be examined and run by anyone, this Model contributes to defensible, robust, and transparent decision making.

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