

**LESSONS LEARNED: MONITORING AND MAINTENANCE EXPERIENCE AT
COMPLETED
URANIUM MILL TAILINGS SITES, UNITED STATES**

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ABSTRACT

There are over 40 uranium mill tailings disposal sites in the continental United States. Remediation is complete at 23 of these sites. The remaining sites will be completed by about 2020. The oldest disposal cells were completed in 1985-86 and are now 12 to 13 years old. Experience with surveillance, monitoring, and maintenance at these sites indicates that passive, "no maintenance" designs are a worthy objective but difficult to achieve.

The disposal cells are so far successful. The oldest cells, built over 12 years ago, are performing well. No tailings, once buried, have been exposed; and no groundwater has been contaminated as a result of contaminants leaching out of the disposal cells. However there have been problems, chiefly problems that threaten the continuity and permeability of the cover materials placed over the tailings.

1. Disposal cells are conceptually closed systems. After construction, natural processes quickly tend to open them. Therefore, maintenance and repair will be required if the disposal cell is to survive, under the best circumstances, for more than a few years.
2. The engineering design of the disposal cell must anticipate the encroachment of vegetation. It may be difficult or impossible to prevent or control. To ensure the longevity of the disposal cell and to control maintenance and repair costs, the disposal cell should be designed to anticipate plant encroachment and take advantage of it.
3. Teams that design and build disposal cell must include personnel familiar with erosion control techniques, revegetation of disturbed areas, and evapotranspiration cover designs.
4. Slopes and drainage systems that surround disposal cells are part of a geomorphic continuum. Construction of an above-grade disposal cell is likely to cause or accelerate erosion that may eventually threaten the disposal cell.
5. Use of poor or marginal quality materials in disposal cell covers is inconsistent with a low- or no-maintenance disposal cell design.

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INTRODUCTION

There are over 40 uranium mill tailings disposal sites in the continental United States. Remediation is completed at 23 of these sites. The remaining sites will be remediated by about 2020 or thereafter. Remedial action at these sites includes decontamination of the mill and surrounding land, and isolation of tailings and associated contaminated materials in specially designed disposal cells. The oldest disposal cells were completed in 1985-86 and are now 12 to 13 years old. This paper summarizes the U.S. Department of Energy's experience at several of these disposal cells.

Surveillance, monitoring, and maintenance of completed uranium mill tailings disposal cells in the United States is the responsibility of the U.S. Department of Energy (DOE) Long-Term Surveillance and Monitoring (LTSM) Program, established at DOE's Grand Junction Office (GJO) in 1988.

The mission of the LTSM Program is (1) to assume long-term responsibility for the disposal sites after they are remediated, and (2) to assure regulatory compliance and long-term integrity and safety, or long-term performance, of the disposal cells; or, in other words, to ensure the long-term isolation of tailings to protect public health and the environment. This responsibility includes annual site inspections, site security, groundwater monitoring, maintenance and repair, emergency response, annual reports, records management, and communication with regulators, local governments, and the public. At selected sites, radon monitoring and operation of water treatment and leachate collection systems will also be required.

SITES

In most cases, disposal cells are at or near former uranium mills built near the uranium mines. In a few cases, such as sites in Pennsylvania, ore was transported a long distance to make use of an existing milling facility. Most sites are in relatively remote, rural areas where few people live. Some sites are notably urban.

Disposal cells vary in size from 4 hectares to over 300 hectares. Volume of tailings in the disposal cells ranges from approximately 70,000 m³ to 19,800,000 m³. Level of radioactivity in the disposal cells ranges from approximately 40 Curies (Ci) to 128,000 Ci (estimated total activity).

Contaminants in the disposal cells are low-level radioactive wastes (tailings, slimes from settling ponds, contaminated equipment, building materials, and soils). Primary contaminants are uranium and thorium daughters, nitrate, and heavy metals considered toxic. A few sites also contain small quantities of polychlorinated biphenyls (PCBs) and asbestos. (Chemicals, like PCBs and asbestos, are placed in uranium mill tailings disposal cells only if they are associated with the tailings as "process-related wastes.")

Most disposal cells are surface impoundments, hill-like, with positive relief. Natural swales or small valleys were used for some sites, in which case the disposal cell may be low profile with little relief.

REGULATORY ENVIRONMENT

Uranium mill tailings disposal cells in the U.S., remediated under the Uranium Mill Tailings Radiation Control Act (UMTRCA) and regulated by the U.S. Nuclear Regulatory Commission, are under four principal regulatory constraints: (1) longevity, (2) passive design, and limitations on (3) escape of radon and (4) the leaching of radioactive and metal contaminants.

Longevity. Disposal cells are to last for 1000 years; and if that is not achievable, for a minimum of 200 years. The 200-to-1000-year design life is a political objective, as well as a technical objective. It is a political objective in that no government has lasted for 1000 years without change or periods of instability. Whether or not any government, or succession of governments, can provide “institutional control” for 200-to-1000 years remains to be seen.

Passive, No-Maintenance Design. The second constraint is a passive design, a design for which there is reasonable expectation that the disposal cell will survive for 200-to-1000 years without the need for active or planned maintenance. What constitutes a passive, no-maintenance design is open to interpretation; and the concept has been applied somewhat differently at some of the sites. The LTSM experience is that some maintenance is required very soon after construction at most sites. None of this work was anticipated. Accordingly, the cost was also not anticipated. And these costs are likely to continue, and may increase; because many, if not most, disposal cells may not survive in their intended condition for 200 years without this maintenance and repair.

Disposal cells are conceptually closed systems: They are built to **contain** waste materials indefinitely. In reality, natural processes that tend to “open” the system quickly develop. The entropy argument is that it takes energy to build such an ordered system; the system will begin to deteriorate and return to disorder once the energy is withdrawn. The preferred strategy is to design and build disposal cells that take advantage of inexorable long-term natural changes. To ensure the longevity of the disposal cell and to control the cost of maintenance and repair, disposal cells should be designed to take advantage of natural changes rather than be a barrier against them.

Elected and administrative officials at all levels of government, many of whom are not technically trained, may be disappointed to learn that the cost of a disposal cell is not just the one-time cost to build it. Funding to maintain the site must also be anticipated and provided; and these costs may be hard to estimate or forecast accurately because of the many variables involved, at least some of which may not been foreseen or anticipated in the engineering design.

Lesson Learned No. 1: Maintenance and repair may be required in the years after the disposal cell is built. This possibility must be recognized and funding provided, if, under the best of circumstances, the disposal cell is to survive, as built, for more than a few years.

Radon Release. The regulatory limit on release of radon to the atmosphere is 20 pCi/m²/sec. This measurement can be area averaged over the entire surface of the disposal cell. An occasional higher reading or "hot spot" is allowed. To meet this standard, the disposal cell must have a cover

over the tailings that limits the release of radon to the 20 pCi/m²/sec standard for the lifetime of the disposal cell. Measurements of radon flux immediately after disposal cells are built are usually less than 1 pCi/m²/sec.

Radioactive Materials and Metals Release. In addition to limiting the release of radon, the design of the disposal cell must achieve long-term containment of (1) radioactive materials, chiefly uranium daughters and (2) associated toxic metals. If meteoric water flows through the disposal cell cover, leaching will doubtless occur; and contaminants, as leachates, will move into surrounding soils, groundwater, and surface waters. (Contaminants can also be released by (1) uptake and transport through the vascular system of deep-rooted plants and (2) tailings brought to the surface by burrowing animals. Neither is a problem at U.S. sites at this time.)

Standards, referred to as Maximum Concentration Limits (MCLs) for release of radioactive and toxic metals, are established by the U.S. Environmental Protection Agency. Groundwater monitoring for contaminants with MCLs is required at some sites for lengths of time that vary from a few years to indefinitely. This too is a cost item that must be anticipated and funded.

Increasing concentrations of contaminants, concentrations above MCLs, is occurring in groundwater at two disposal sites. The problem is under study. At this time, the problem is not related to maintenance or repair of the cover materials that overlie the tailings.

STRATEGY

The strategy to achieve the four constraints discussed above is to preserve the radon barrier that is part of the engineered cover that overlies the tailings. The cover, including the radon barrier, must survive erosion, prevent release of radon, and prevent meteoric water from flowing through the disposal cell and leaching contaminants to surrounding groundwater and soil for the required 200-to-1000 years. (At some sites, the radon barrier is referred to as a "compacted soil layer" (CSL).

DISPOSAL CELL DESIGN

The surface of the disposal cell may be (1) entirely rock-covered (in dry climates), (2) vegetated and partially rock-covered, or (3) completely vegetated (in humid climates) to prevent erosion.

Riprap is used at many sites to prevent erosion of underlying layers, including the radon barrier. The size of the rock, or D_{50} , is determined by the sheet flow that would result from the Probable Maximum Precipitation (PMP) or Probable Maximum Flood (PMF) event. D_{50} is the diameter of rock, such that half, or 50 percent, of the rock, by weight, must be larger. Catastrophic floods or precipitation, worse than the design PMP or PMF, is considered an acceptably rare risk at U.S. sites.

In humid climates, plants growing over a thick soil layer is considered a reliable means of erosion protection for the 200-to-1000-year lifetime of the disposal cell, although deep-penetrating root systems of some plants continue to be a concern and the design must take account of them.

Changes in climate, due perhaps to global warming, might alter the vegetation; but the change is expected to occur slowly. Geographic shifts in vegetation may actually lag climate change by decades or even centuries. Under most scenarios, the new plant succession would likely be equally successful in preventing erosion, unless the climate change were in the direction of excessive drying.

Below the erosion protection layer, there may be several underlying layers above the radon barrier, each layer with a specific purpose. The more complex designs may incorporate such layers as, lateral drainage, bedding, root protection, frost protection, and capillary barrier layers above the all important radon barrier. These layers together with the radon barrier constitute the "cover" that overlies the buried tailings.

The radon barrier has two important functions: (1) to limit the release of radon into the atmosphere below the 20 pCi/m²/sec standard, and (2) to prevent meteoric water from entering the disposal cell and leaching contaminants to the surrounding environment (groundwater, surface water, and soils).

The radon barrier is, typically, a clay-rich, naturally occurring soil that can be compacted to a saturated hydraulic conductivity value, K_{sat} , of 1×10^{-7} cm/sec or less. This value is empirical and based on the compaction that can generally be achieved in naturally occurring clay-rich soils. Bentonite is mixed with the clay-rich soil at some sites where sufficient quantity of compactible soil is not locally available or to reduce the cost of construction by reducing the thickness of the radon barrier. In semiarid regions, the radon barrier is typically "dry" or unsaturated. In humid regions, the radon barrier is more likely to be saturated, at least seasonally. At some sites, evapotranspiration may be sufficient to dry out the radon barrier, in whole or in part, at different times during the year. Saturated, seasonally saturated, or unsaturated conditions are acceptable as long as the flow of meteoric water through the radon barrier, when it occurs, is at rates of 1×10^{-7} cm/sec or less. Should that rate increase over time, it would be a concern.

Thickness of the radon barrier varies from disposal cell to disposal cell and ranges from about 45 cm to 215 cm. The thicker radon barriers were installed at the earlier and now oldest disposal cells. Such thickness was subsequently determined to be excessively conservative. Thinner, 45 cm-thick radon barriers, are typical of the newer sites. (Required thickness of the radon barrier is

computed using the NRC's RADON model. An earlier version of this model, RAECON was used to determine the thickness of the radon barrier at the earlier sites. This model has been refined several times. Refinements have allowed thinner radon barriers to be installed in the newer covers.)

Protection of the radon barrier from erosion and root damage is the primary challenge to long-term performance and regulatory compliance of the disposal cells.

BIOINTRUSION

Biointrusion includes animal burrowing and encroachment of deep-rooted plants on the disposal cell. So far, burrowing has been only a potential or hypothetical problem. It has occurred at a few sites, but the burrowing was not extensive and the animals did not establish permanent colonies on the disposal cell.

Biointrusion by deep-rooted plants is a serious concern at several disposal cells and may eventually be a concern at most. If roots perforate the radon barrier in sufficient number, the design K_{sat} , 1×10^{-7} cm/sec, is likely to increase, and the initial relative impermeability achieved by compaction will be compromised.

The Burrell, Pennsylvania, disposal cell was completed in 1987. Field measurements at the Burrell disposal cell show that plant roots (and perhaps some related soil forming factors) have increased the K_{sat} to 10^{-5} cm/sec. Comparative measurements taken at a nearby analog site, an historic site undisturbed since the late 1800's, show that the plant succession (hardwood forest with little understory) is likely to increase the K_{sat} to 10^{-4} cm/sec in a short period of 100 years or so.

Values of K_{sat} in the range of 10^{-5} to perhaps 10^{-4} indicate that the Burrell disposal cell is, technically, out of compliance with respect to the design specification of $K_{\text{sat}} = 10^{-7}$ cm/sec. This is a concern. The goal is to design, build, and maintain sites so that they perform to the design specification. What are the consequences, in terms of risk, if they do not?

At Burrell, attempts have been made to control vegetation so that the K_{sat} does not degrade further. These attempts have not been successful. Control has relied on agricultural-strength systemic herbicides, which themselves are hazardous chemicals. The plants in the humid climate at Burrell are aggressive; and the "kill", using herbicides, has always been incomplete and short-lived. The same plants often return within the same growing season.

Continued use of herbicides at this site is no longer acceptable. Not only are the herbicides ineffective, the chemicals are hazardous and constitute an environmental risk in themselves. Use of hazardous chemicals on such a scale is to introduce a new risk in attempt to control an existing risk. Clearly, both risks need to be evaluated. (Nor is it certain that the application of these chemicals on an annual basis for a minimum of the next 188 years is institutionally sustainable.) The proposed solution is risk assessment. Risk assessment, currently underway, is to determine

if the measured and expected increases in the K_{sat} actually pose a risk to public health and the environment. The risk assessment will look at (1) rates of water movement through the radon barrier as it degrades in response to root penetration, and (2) the concentrations of radon and leachable contaminants that may leave the disposal cell as K_{sat} increases to the anticipated 10^{-4} cm/sec value. Pathways for these contaminants to reach the biosphere will be then identified, evaluated, and exposures calculated.

It is expected that, in the worst case, the pathways-based risk will be acceptably low because the disposal cell does not contain high levels of radioactivity. If so, DOE will propose an end to vegetation control and acceptance of the disposal cell with increased permeability of the radon barrier. If NRC and stakeholders agree that risk is acceptably low, the site will be allowed to return to hardwood forest.

If risk(s) are unacceptably high, or if allowing the forest to reclaim the site without further intervention is unacceptable to the public, use of hazardous chemicals in an attempt to slow the encroachment of deep-rooted plants will likely continue despite the unplanned cost and potential problems associated with release of hazardous chemicals into the environment. Modification of the design of the disposal cell to compensate for the forecast increase in K_{sat} may also be considered. An option might be to install a thick soil layer over the existing cover. This layer would allow the forest succession to occur without further damage to the radon barrier.

Lesson Learned No. 2: The succession of natural vegetation, especially in humid climates, is bound to occur and difficult to control. Nature will have its way. Disposal cell designs must anticipate that (1) vegetation will encroach on the disposal cell, (2) some of this vegetation will be deep-rooted, and (3) the best, or least maintenance, design will either isolate the encroachment from the radon barrier or incorporate the vegetation to some advantage, such as using evapotranspiration to de-water the radon barrier, so that the vegetation is an asset to the long-term performance of the disposal cell.

EROSION

A disposal cell, properly designed, constructed, and maintained, will shed most of the water that falls on it as rain or snow. This can be a lot of water. A 13 cm rain, common at some U.S. sites, falling on a 39 hectare cell produces approximately 50,000,000 L of runoff. If the cell sheds most of this water, as it should, the water moving off the cell into both as-built and natural drainage channels will be substantially more than if the moisture falling on the cell soaked into the cell at the same rate as in naturally occurring soils. The potential for erosion from this increased runoff is significant.

Erosion caused by runoff has not occurred **on** any disposal cell so far. (Minor wind erosion [deflation] has been occurred at two sites, sites that incorporate soil or a soil-rock mixture as part of the cover design. This erosion is now stabilized by the formation of an armored, desert pavement-like surface, and measurable deflation is no longer occurring.)

Disposal cells are designed to shed rainwater and snow melt efficiently without erosion, and so far they are doing so. The erosion that has caused problems is erosion around the edge or apron of the disposal cell or on neighboring property. The problem has been that erosion around the disposal cell, by head-ward migration of rills and gullies, has threatened to move into the edge of the disposal cell. DOE has intervened at several sites to prevent erosion from damaging the cover and exposing once-buried tailings. Without this intervention, it is not clear that erosion would have stabilized or stopped before exposing tailings, or worse, transporting tailings downstream away from the site.

The Lowman, Idaho, disposal cell is in a mountainous region with abundant snowfall and often heavy runoff from rapid snowmelt. Short but intense summer thunder storms are also common. The climate is savannah with large pines and thick, grassy understory. The disposal cell was completed in 1991.

The disposal cell is covered with angular granite riprap. The graded and disturbed areas around the disposal cell are steeply sloped. The soil on these slopes is a friable, weathered bedrock (grus) with little organic material and no developed soil horizons. After final grading, these slopes were planted with annual grasses to hold the soil against erosion until native species could establish. The effort was not successful. Annual grasses sprouted the first season, but not thereafter. Native vegetation did not establish. Gullies began to form within one year (1992).

Erosion became an issue in 1996, when gullies, some as large as 3 m deep and 10 m long, were noted. Headcuts in these gullies were migrating up-slope and rills above these headcuts began to reach into the edge of the disposal cell. Intervention was required.

In October 1998, the eroded areas were regraded to fill the gullies and headcuts. Drainage terraces were installed to convey water across slope and off site. The entire area was replanted by hydroseeding over a hydromulch. Cost to repair this erosion, approximately \$70,000, far exceeds what it would have cost to terrace and more carefully revegetate at the time the site was under construction in 1991.

Conceptually, erosion peripheral to the disposal cell is an “edge” effect. Areas around the edge of the disposal cell begin to erode because they were not properly designed, graded, revegetated, or otherwise protected from erosion. Erosion around the edge of the disposal cell increases until it directly threatens the disposal cell. This has occurred at several sites, the Lowman site being the most serious example.

Lesson Learned No. 3: Personnel experienced with erosion control techniques and revegetation of disturbed areas must be part of design and remedial action teams. These persons must have authority to participate in the approval and acceptance of final site designs and to oversee the site while it under construction.

Lesson Learned No. 4: Slopes around and below the disposal cell must be understood to be part of a geomorphic continuum. A change at one place along the slope, or the construction of a

positive feature, such as a disposal cell, on a previously stable slope, will cause slope adjustments (erosion) and some of these may eventually threaten the disposal cell.

DEGRADATION OF RIPRAP

The Lakeview, Oregon, disposal cell was built in 1989. It also is in a mountainous area. Winters are wet, summers are dry except for thunder storms. The radon barrier cell is protected from erosion by a rock and soil mixture on top of the disposal cell and by riprap on the long, west-facing side slope of the disposal cell. Plant encroachment on the rock and soil mixture on top of the disposal cell is a potential problem currently under study, but the bigger problem is the condition of the riprap on the side slope.

The riprap is a weathered olivine basalt. The design called for a riprap layer 15 cm thick with a D_{50} of 7 cm. Inspectors at the quarry noticed that some of the rock was cracked and crumbling as it came from the quarry wall. Much better rock, a densely crystalline basalt, was available from a quarry 150 km away. To contain cost and maintain construction schedule, both of which would have been adversely effected by a 150 km haul, decision was to use the weathered, poorer quality basalt but to double the thickness of the riprap layer and to use somewhat larger rock than the minimum required. Doubling brought the as-built thickness to approximately 30 cm.

The riprap was installed in 1987. In 1994 it was noticed that numerous stones were cracking and splitting or spalling as they lay in place on the surface of the disposal cell. The rock was deteriorating under surface weathering conditions. Petrographic examination of the rock showed that the rock was microfractured throughout, the glassy matrix and feldspar crystals were cloudy and altering to clay, and olivine was altering to iron oxides along edges and fractures.

The rock was weathering so fast that, in 1996, a procedure to measure the rock and monitor its decrease in size was instituted.

The design at Lakeview called for a D_{50} , such that 50 percent of the stones, by weight, must be larger than 7 cm. Riprap 7 cm to 10 cm in diameter was installed to meet, conservatively, the 7 cm requirement. Measurement of the rock in 1997 and 1998 showed the mean diameter of the riprap had decreased, due to weathering, to about 7 cm. Thus, the riprap was at the lower limit of the design requirement. (Doubling the thickness of the poor quality riprap was not a good solution. Part of the function of large diameter rock is to provide "roughness" to dissipate the energy of overland flow. A double thickness of poor quality rock eventually becomes a double thickness of small rock, and this does not achieve the required weight or roughness.)

The size of the riprap is now borderline. Weathering of the riprap is expected to continue. When the riprap breaks down to the point that the D_{50} is less than the design requirement, intervention may be necessary. Options include (1) recalculation of the statistical PMP to confirm no errors were made, (2) argument that the statistical PMP is inappropriate for the location of the disposal cell, (3) pathways-based risk assessment, as discussed above for the disposal cell at Burrell, and (4) redesign and reconstruction of the disposal cell cover. The latter might include the addition

of more, better quality riprap or installation of deep soil and revegetation. The cost for this option could be in the \$1,000,000 to \$2,000,000 range. Such cost, to maintain and repair a disposal cell after it is built, is unprecedented.

Lesson Learned Nr 5: Use of poor or marginal quality materials is not consistent with a low- or no-maintenance disposal cell design.

CONCLUSION

A passive, no maintenance disposal cell design is a worthy objective. It is difficult to achieve.

The disposal cells built in the U.S. for uranium mill tailings are so far successful. The oldest, built over 12 years ago, are performing well. No tailings, once buried, have been exposed, and no contamination of groundwater has been recorded as a result of leaching from the disposal cells.

However there have been problems, chiefly problems related to maintenance and protection of radon barriers as installed.

1. Disposal cells are conceptually closed systems. In reality, natural processes, that tend to “open” the system, quickly develop. Energy is spent to construct the containment system; containment begins to deteriorate once the energy is withdrawn. Therefore, maintenance and repair will be required to preserve the life of the disposal cell and its ability to contain waste materials. Governments and agencies that provide environmental oversight must understand that maintenance will be required and that there must be a source of funding for this work if the disposal cell is to survive, under the best circumstances, for more than a few years.
2. The engineering design for the disposal cell must anticipate the encroachment of vegetation, especially in humid climates. The natural succession of vegetation will occur; and if it is deemed undesirable, it will be difficult to control. Engineering designs must anticipate that (1) vegetation will appear on the disposal cell, (2) some of this vegetation will be deep-rooted, and (3) the best (least maintenance) design will use the vegetation in a way that will be an asset to the long-term performance of the disposal cell. The preferred strategy is to design and build disposal cells take advantage of long-term natural changes and natural processes, such as evapotranspiration. This is the only practical way to ensure the longevity of the disposal cell and to control maintenance and repair costs.
3. Teams that design and build disposal cell must include personnel familiar with erosion control techniques, revegetation of disturbed areas, and evapotranspiration cover designs. These persons must have authority to participate in the approval and acceptance of final site designs and to oversee the site while it is under construction.
4. Slopes and drainage systems that surround disposal cells must be understood to be part of a geomorphic continuum. A change at one place along a previously stable stream bank or

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hillslope, such as the construction of an above-grade disposal cell with positive relief, is likely to cause or accelerate erosion that may eventually threaten the disposal cell.

5. Use of poor or marginal quality materials in disposal cell covers, such as poor quality rock for erosion control, is not consistent with a low- or no-maintenance disposal cell design.