WASTE DISPOSAL CELL COVERS:

PRACTICE, PROBLEMS, & OPPORTUNITIES

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ABSTRACT

A series of disposal cells and in particular the covers used to remediate sites that contain radioactive, hazardous, and toxic waste are described. The site locations are all in the arid west. While the regulations that govern the design and construction of these many covers vary greatly, the case histories show that a similar engineering approach is adopted regardless of the laws that establish performance criteria. The case histories are the basis of suggested norms or desiderata to govern the design, construction, and maintenance of long-term covers. The research that must be undertaken to confirm the performance of long-term covers and to improve the state-of-the-art of cover design are discussed.

INTRODUCTION

This paper describes covers for remediating sites and for encapsulating radioactive, hazardous, and toxic wastes. The focus is on covers for facilities that encapsulate radioactive and hazardous waste, because that is what I have worked on in the past decade. Before that my work was mainly on mine waste disposal facilities, tailings impoundments, and waste dumps. Much of what is recorded here is applicable to mine waste disposal facilities. Now my projects include municipal waste facilities. Much of what is said here is also applicable to such facilities. They are not discussed in detail here because the issues are complex and controversial. Let those topics await another venue.

The designer of the cover for a long-term waste encapsulation facility must consider and account for the nature of the site; the characteristics of the waste; the availability of suitable construction materials; and, above all, the need to protect human health and the environment for as long as practical and possible. Research and development are key to the development and adoption of better designs which will endure for a long time. In addition, the designer must show that the design complies with local regulations; or, if these are manifestly illogical or inappropriate, the designer must persuade society and the regulators to adopt better design norms. Research and development are key to the development and adoption of better design standards and norms.

Disposal cells and covers for waste are required in order to encapsulate the waste, hinder intrusion to the waste, prevent inadvertent waste dispersal, control infiltration and radon flux, and limit distress and damage of the cell by extreme natural forces. The multiple components of the cover encapsulate the waste. Institutional controls on access to the site deter intrusion. To provide for loss of institutional control, many covers incorporate a thick layer of gravel and boulders. This layer should provide reasonable notice to intruders that unusual conditions lie beneath. In addition, the boulders and gravel inhibit root penetration and the advance and passage of burrowing animals. Infiltration through the cover to the waste is controlled by one or more layers of low permeability soil or geosynthetic layers such as a high density polyethylene geomembrane. Radon exhalation is controlled best by a layer of compacted silt and clay; this impedes upward passage of the radon gas that decays en route through the clay and silt layer.

To control erosion of the cover layers by precipitation runoff, gravel may be placed as the uppermost layer of the cover. In some areas a soil layer in which vigorous vegetation will persist is used to control and moderate the effects of erosion. To prevent slope instability induced by static or dynamic forces, the inclination of the cover must be sufficiently flat to preclude sliding or creep movement off the waste.

Because this paper is presented to an audience of students and academics, I try to focus on those things I do not know, which are yet to solved, and where there are possibly valid and valuable research and development opportunities. My perspective is that of a practitioner; I make my living solving clients' problems and building things. If I focus more on the practical and less on the theoretical, that is because that is where I need answers. But I have tried to sketch those opportunities I suspect exist for pure research.

STANDARDS AND DESIGN CRITERIA

The regulations and standards that govern the design and construction of the covers for radioactive and hazardous waste facilities vary greatly from state to state and from regulatory agency to regulatory agency. Consider, for example, the design life. The least demanding standard calls for a commitment to 30 years of monitoring and maintenance; the most demanding calls for assured performance for 1,000 years to the extent reasonably achievable.

Some of the standards say nothing about monitoring and maintenance; others call for a design that minimizes the need for maintenance. As noted below, I believe that the need for long-term maintenance is inevitable, and should be dealt with at a national level; the most the design engineer can do is minimize the need for extensive maintenance.

Some of the standards lead inevitably to a need to design for the maximum credible earthquake and the probable maximum precipitation. Others talk of remaining stable for 100 years, a criterion some have - mistakenly, I believe - interpreted to mean designing for the 100 year recurrence interval earthquake and precipitation.

Some of the standards call for a minimum infiltration. Others mandate the use of geomembranes. The U. S. Nuclear Regulatory Commission refuses to accept geomembranes as a valid way to control infiltration; they believe that these geomembranes will soon deteriorate and render the covers nonfunctional.

In most instances the standards do not reflect a genuine technical, societal, or environmental need or requirement. Generally, they are a compromise between the politically opposing forces of those who would impose the most demanding requirements possible, as a matter of philosophical conservatism, and those who are faced with paying to implement the standards.

RECOMMENDED DESIGN NORMS OR STANDARDS

The following norms may be used to guide what is proper and necessary to remediate disposal facilities that contain and encapsulate radioactive, hazardous, or toxic waste; in most instance these should also apply to landfill covers.

- The design life should be as long as economically feasible, and certainly no less than 200 years.

- The design life should equal to the period of noxiousness of the encapsulated waste up to 1,000 years and beyond if technically practical.

- The encapsulation facility should be designed to remain stable and not allow for dispersal of the waste in the event of extreme events; these should be consistent with the facility design life, surveillance and maintenance plans, and the risk and implications of failure. Appropriate design events are the maximum credible earthquake and the probable maximum precipitation.

- The cover should be designed to reduce infiltration to the waste to 10^{-7} cm/sec or less; greater infiltration may be acceptable if no adverse impact results.

- The encapsulation facility should be designed to deter and impede human, animal, and plant intrusion; minimum maintenance should be involved in retaining the integrity of the facilities.

APPROACHES TO TECHNICAL AND ENGINEERING DESIGN DETAILS

Existing wastes deposits may be stabilized in place, exhumed and stabilized on site in new disposal cells, or exhumed and relocated for disposal off site. The decision to stabilize in place, stabilize on site, or dispose off site is made on the basis of local socioeconomic considerations and site suitability. I suggest the following norms for selecting one or the other of these stabilization and disposal options.

- Stabilization In Place: Acceptable if the site is not in the probable maximum flood plane or over an active fault or potable aquifer. Foundation subsoils must have sufficient geochemical attenuative capacity or the groundwater must be adequate to indefinitely prevent adverse impact on groundwater quality and potential receptors; this may be quantified either by groundwater quality standards or acceptable risk or dose to receptors.

- Stabilization On Site: Acceptable if the site meets criteria for Stabilization In Place. To be used if exhumation of the waste is necessary to characterize them, treat them, or place them in a facility such as a lined encapsulation disposal cell.

- Disposal Off Site: Acceptable if transport does not involve unacceptable risks to those through whose neighborhood material is moved; also a suitable, and much more stable, site must be economically available. Selection of Disposal Off Site simply to put the waste in somebody else's backyard is not acceptable. Those in the neighborhood of the site generally benefitted in the past from its presence; having enjoyed that part of the bargain they must now accept the complete pact.

While the details of covers may differ, I suggest they involve the following technical approaches that constitute acceptable engineering norms.

- Use only natural materials such as soil and rock; do not use, or at least do not rely, in the long-term, on geosynthetics.

- Provide at least one and preferably two components to fulfill each functional requirement. Multiple redundancy of function is preferred.

- Select only the most durable rock available; and if such rock is not available, provide adequate thicknesses of soil to fulfill the same function.

- Use very conservative design assumptions and technical and analytical approaches; always ask what the worst is that can happen and provide components to prevent or mitigate potential consequences.

If a new disposal cell is built at a new site for radioactive or hazardous waste, I believe that the site selected should be such that a basal liner system is not required. The natural foundation soils and rock should be adequate to protect groundwater quality in the long term. Geochemical attenuation or dilution should be such as to achieve this requirement. If the new site requires a basal liner to protect groundwater, it is probably the wrong site and should not be used. I recognize that this recommendation may not be implementable in certain jurisdictions that mandate liners. I believe such regulations are illogical, are based on consideration of encapsulation of waste that will be noxious for but a short time, and fail to consider the inevitability of basal liner failure and subsequent seepage from the bottom of the cell.

If a new cell is built at an existing site, I am prepared to accept the need for a basal liner as a way to enhance protection of site groundwater and as a way to secure regulator and community acceptance of the new on site cell. I believe, however, that the designer must do all that is possible to ensure that when the basal liner system fails, as is inevitable, that the groundwater will not be negatively impacted. In addition, I recommend that the designer ensure that those responsible for the cell recognize the absolute need for perpetual and continual operation and maintenance of the leachate collection system and possibly treatment of seepage from the cell.

CASE HISTORY 1 - THE URANIUM MILL TAILINGS REMEDIATION PROJECT

The first major project is the U.S. Department of Energy's Uranium Mill Tailings Remedial Action (UMTRA) Project. This project involves remediating 24 sites in 10 states, primarily in the west. At about half the sites, the radioactive tailings were removed and relocated to alternative sites; at the other half, the tailings were shaped and covered in place. In no case were liners used. The cover is the only engineering component used to encapsulate the wastes.

At most western UMTRA sites the cover consists, from the waste up, of a compacted low permeability clay/silt layer that impedes water infiltration and radon flux, a sand layer that acts as a drain, and durable rock sized to resist erosion by runoff from the probable maximum precipitation.

Design issues that continue to be of interest in these covers include: the relationship between the moisture content of the partially saturated clay/silt layer and its hydraulic conductivity; the radon diffusion coefficient of the clay/silt layer; the long-term equilibrium moisture content of the clay/silt layer; the influence of the overlying sand and rock on the moisture balance in the clay/silt layer; the potential for erosion of the clay/silt by water seeping off the cover through the sand drain; the potential for cracking of the clay/silt by waste deformation, freeze/thaw, or desiccation; the durability of the rock; and the potential for the self-establishment of vegetation in the rock. More than half of the 24 sites have been remediated and monitored for up to 8 years. A considerable amount of information on the performance of these covers is accumulating. The only significant occurrence is that at some sites vegetation is self-establishing on the covers.

The UMTRA cover built at the Durango, Colorado site consists of these components, from the waste up: a radon and infiltration barrier of silty clay; a layer of Claymax which is a 25 mm thick layer of bentonite between two geotextiles; a clean sand drain; a biointrusion zone of cobbles; a filter layer of gravel; and soil, the upper lift of which contains abundant gravel to enhance erosion resistance. This cover was selected to enhance infiltration control, and to minimize biointrusion. It has been in place for more than five years and is performing well: no erosion has occurred, shallow rooted vegetation is growing and infiltration from the cell is as calculated. A cover similar to this has been adopted for a demonstration and trial project at the Hanford Site in Washington State. For that cover a layer of asphalt is used in place of the Claymax; otherwise there is no significant difference between the two covers.

An enormous body of both theoretical and practical experience has been accumulated on the UMTRA Project. Much of it is buried in the project files; little has been written and published in an easily accessible format. This is a unfortunate, but it represents a true opportunity for the engineer or scientist with an interest in technical history and the interaction of personalities and the development of engineering science.

CASE HISTORY 2 - PROPOSED NEVADA COVER

A cover proposed for remediation of radioactive waste disposal facilities at an extremely arid site in Nevada would incorporate these components, from the waste up: a 1-m thick layer of soil-cement formed with local sand; a layer of Claymax; a drain of sand formed by washing local soils; 1 m of random local sand and silt; and another 1 m of local soil to which gravel is added to enhance wind and water erosion resistance.

Neither good quality rock or clay are economically available at the site. Local evapotranspiration greatly exceeds precipitation, and vegetation is sparse to non-existent. In addition those responsible for the sites are willing to undertake indefinite continual monitoring and maintenance. Infiltration is controlled by evapotranspiration from the upper soil layers; the bentonite layer will limit infiltration of any seepage through this upper layer. I am not concerned about cracking induced by either waste deformation or desiccation; the bentonite will swell and essentially close up if and as water reaches it. Biointrusion control is achieved by the thick layer of soil, the soil cement, and by maintenance. Wind and water erosion control is achieved by the gravel added to the upper soil layers. In addition, the soil cement will bridge potential voids that may occur as the waste deteriorates.

This cover is yet to be designed. Some valid questions that the designers ask include: what are the properties of the soil cement now and in the long term, and how will it respond to the heat and dryness of the desert; how will this cover materials respond to seismic disturbance; what is the capacity of the soil cement layer to bridge voids that may form in the waste; how can money be saved by using local materials and reducing layer thicknesses; how thick an upper soil layer is required to limit infiltration; can we rely on capillary action at the interface of the soil and sand; what vegetation will self-establish and flourish and how can it be controlled. I suspect that the eyes of a good geologist and geomorphologist will find the answers to these and other question in a study of the local landscape.

CASE HISTORY 3 - PROPOSED CALIFORNIA LANDFILL COVER

In southern California is a landfill used primarily for municipal-like waste. There is some evidence that other wastes were disposed in the landfill and that these may be the source of contamination of the partially saturated zone and groundwater beneath the landfill.

The wastes were disposed of in a series of long parallel trenches separated by the in situ dense earth. Accordingly there is a potential for corrugated differential settlement to affect a new cover.

The proposed new cover consists of these layers from the waste up: 600 mm of random soil to cover protruding metal and other exposed waste; a geosynthetic clay layer (GCL); 150 mm of clean drainage sand; 1 m of soil to act as a root and animal zone and as a sponge for water held up by the capillary action of the underlying sand; and 150 mm of gravel amended soil to limit wind and water erosion.

The landfill is on a military base; those in charge are committed to an active surveillance and maintenance program. Indeed, they would like to convert the cover to a heavy equipment parking area when funds are available. The long-term use of the site, after potential base closure or abandonment, is not an issue.

Applicable regulations call for a minimum cover of 600 mm of bedding soil, a 300 mm layer of soil with a hydraulic conductivity of 10^{-6} cm/s, and 300 mm of soil for vegetation. Clearly this cover is inadequate in a very hot, dry environment. It will desiccate and the infiltration component will crack; vegetation and animals will rapidly penetrate the upper soil. Wind and water erosion will soon remove the soil, regardless of the results of calculations using the Universal Soil Loss Equation.

The battle rages on the field of engineering philosophy, ethics, morality, regulatory compliance and practical cost consideration about whether to build the minimum regulatory compliant cover or whether to meet and exceed client expectations by providing something more substantial and robust. The legal philosopher and pragmatic regulator might well join with the engineer and scientist to examine the policy and cost issues that the alternate covers embody.

SOME ISSUES AND FUTURE DIRECTIONS

Much additional research into the best design of a long-term robust cover for radioactive, hazardous, and toxic waste is ongoing. Much more such research is required. In this section, I would like to summarize some of the work in progress and suggest ideas for possible future research. I do not link these to the specifics of the case histories I have described; I simply group issues and ideas as they occur to me.

Innovative Cover Components

A promising idea is the use of high air permeability gravel layers oriented to create air movement through and hence drying of the layer and the cover. The gravel layer would be placed beneath the soil. Air movement induced either by fans or the geometry of the cover enhance removal of moisture from the gravel; this considerably limits the amount of water that might otherwise infiltrate to the waste. I do not like the idea of fans, unless the period of waste noxiousness is short. I prefer the idea of induced air flow resulting from cover geometry. Another possibility to induce air flow in the gravel is to create thermal gradients by selective use of rocks of different colors, hence heat retention at the inlet and exit of the gravel layer. Also it might be possible on high waste piles to use differential wind velocities at the top and bottom of the pile to induce significant flow in the gravel layer.

Cover Components Materials

We need to identify and research new materials for cover construction. One new material that may be used beneficially in covers is a mixture of sand, bentonite, and glass fiber or long-fiber asbestos. Preliminary testing shows that if the sand voids are just filled with bentonite, the mix has the high strength of sand but the low permeability of bentonite. The fibers would provide tensile strength that enhances stability of steep sideslopes of cells where slope flatten is not practical. This soil mix could be placed either as a conventional soil layer, 150 mm or thicker; alternatively it could be placed as a filler between two geotextiles, as is currently done for some GCLs.

A Non-Vegetative Cover

The following cover is being considered for a new mixed waste disposal cell: an infiltration and radon barrier of silt and clay; a second infiltration barrier of Claymax; a fine gravel drain; a filter layer of sand; and up to 1.0 m of 75 mm and coarser gravel. Observations of a similar material sequence on an old embankment at the site indicate that vegetation is unable to establish in the rock. Seeds washed down and trapped on the sand filter, do not possess sufficient inherent energy to grow up through the upper rock layer, deprived as they are of a reliable source of water and nutrients due to the underlying sand and gravel layer.

The research questions associated with this cover include the following: what are the optimum cover component thickness to achieve the postulated functions; is it really possible to completely eliminate the potential for vegetation to establish in such a cover; and will windborn particles clog the upper rock voids, thus creating an environment conducive to the establishment of vegetation.

The Performance of Some Cover Materials

In the early years of my career as an engineer, I designed and monitored the construction of five mine tailings impoundments in southern Africa. Each had a basal drainage system. Soon after construction, a large percentage of the drains of each impoundment clogged. The clogging was not a result of mechanical plugging. Rather, the clogging agent in each case was biological activity. My biologist friends told me that the interface between the sand of the drain and the silts and clays of the tailings was an ideal, moist, oxygen-rich environment suitable for the development of a host of simple life forms.

I know of no similar set of observations on the drains in disposal cells with which I have been associated in north America. I fear, however, that similar clogging may be taking place. In particular I suspect that the drains of the many heap leach pads built by the mining industry are susceptible to biological clogging. I recommend this area of attention to those with an engineering and biological interest. The primary questions are: is clogging occurring; will it occur in the long term; what will its effect be on cover or basal drain performance; how could clogging be avoided or mitigated.

Steep High Piles

A significant long-term cover design problem is that associated with waste facilities where the current sideslopes are as steep as two horizontal to one vertical. Ensuring long-term stability and infiltration control are mutually incompatible requirements; low permeability elements such as clay do not possess sufficient strength to remain on the slopes for long-term static and dynamic conditions. Some ideas that will inevitably have to be seriously considered include the use of deep rooted vegetation such as eucalyptus trees to both stabilize the slopes and promote evapotranspiration to great depth; regular and perpetual replacement of anchored geomembranes; light-weight interlocking concrete blocks attached to pins driven into an underlying soils such as sand-bentonite; significant thicknesses of soil over capillary breaks; the previously mentioned air passage layers; and soils with a gradation that enhances air movement, hence drying, induced by atmospheric pressure pumping.

An alternative cover suggested for slopes as steep as 3:1 to 2:1 is, from the waste up, as follows: an infiltration barrier of roughened geotextile; a bedding and drainage layer comprised of a second geotextile; 300 to 450 mm of soil for vegetation; and a geogrid within the soil to provide tensile resistance to enhance sliding resistance.

Some questions about the performance of such a cover relate to establishing and maintaining vegetation in the thin soil layer, the possibility of excessive erosion of the soil by heavy precipitation and its attendant runoff, and the static and dynamic stability of the cover system at the interface of the geomembrane and the geotextile. In particular, the cover sliding resistance is critically dependent on the "cohesion" or zero-normal-force shear-resistance between the geomembrane and the geogrid. There is no true cohesion, i.e., molecular adhesion or attraction, between the geomembrane and geotextile. Rather the zero-normal-force shear-resistance results from snaring of the extremity fibers of the geotextile by the asperities of the roughened geomembrane.

During construction, placement of the geosynthetics may destroy or negate this fiber snaring (they may be torn or flattened) by the asperities (they may be smoothed or broken). Alternatively, with time, degradation of the geosynthetic materials, initiated at the outer edges of the materials will result in loss of strength of the fibers and asperities. Seismically induced motion, whether vertical or horizontal, may tear, rupture, or separate the geosynthetics and their "appendages."

Another cover suggested for steep slopes is to roughen the surface by grading to form waves or undulations. Over this would be placed a needle-punched geosynthetic clay layer, anchored if necessary with bollards. Angular sand and rock would be placed over the geosynthetic clay layer to form a drain and to control erosion by precipitation runoff. The undulations would be dimensioned to provide addition sliding resistance to the overall cover. The optimum undulation geometry is a nice research topic.

Cover Selection Methodologies

An old professor of mine taught us that the best way to identify a new design for new problem was to immerse yourself in the details for as long as possible; then have a stiff brandy, sleep on it, and select on the basis of gut feel the next morning. I still believe that he was right. But the tenor of the times precludes us from simply choosing. Now I must document with elaborate and objective reasoning each and every decision and selection amongst competing alternatives.

I do not have a good system for comparing and selecting the best cover from amongst a series of alternative covers. I have used multivariate utility analysis to good avail to justify a somewhat arbitrary choice. I have used four-day long Value Engineering Workshops to build consensus for a particular cover amongst people who have disagreed for years. I have done cost benefit studies and used decision trees to allow clients to provide their own answers and follow to the sequentially logical cover.

I am most haunted by one client who said "Select the cheapest cover; the rules will change in the next thirty years, and then I will select an new cover to meet the new rules." He is of course correct. But this should not be the situation. As a nation and as professionals, I must provide and I in turn deserve a more logical and sound approach to selecting the right cover for the job than just getting by on the game of minimal regulatory compliance.

My challenge to you is: stabilize the law; compile laws that set minima, but reward the optimum; define logical ways to identify, compare, and select amongst alternative cover; incorporate selection procedures into professional practice.

Cover and Disposal Cell Performance Assessment Methodologies

The Nuclear Regulatory Commission is considering accepting the use of probabilistic risk assessments of the performance of covers and complete disposal cells or encapsulation facilities to establish the dose to postulated receptors. This is good news and bad news. The theory of probabilistic risk assessment and the use of Monte Carlo analyses is established. It has not been applied, to my knowledge, with any rigor to radioactive and hazardous waste disposal facilities and their design. This must be done and the proper, prudent technical approaches must be established. In particular, we need guidance on acceptable ways to incorporate the benefits of the reality of probabilistic risk and dose assessments without incurring the disadvantages of the excessive data needs and high costs associated with these sophisticated approaches.

A major issue in the deliberations on the use of probabilistic risk and dose assessments is how to frame the regulatory standards for acceptable risk or dose. Current standards all weigh to the conservative side and incorporate the notion of the worst case analysis. Can we "relax" the standards if we compile realistic performance descriptions using proper distributions of the appropriate parameters, and if we do how do we write the regulations?

Perimeter Dike, Basal Liners, and Waste

The topic of this presentation is the cover of the waste encapsulation facility. I must recognize, however, that the total encapsulation facility usually also involves a basal liner system, perimeter enclosure dikes, and treated waste. Satisfactory long-term performance of the encapsulation system depends as much on the design and construction of these facility components as on the design and construction of the cover.

There are as many research needs and opportunities associated with the perimeter encapsulation system, the basal liners, and waste treatment as with the cover. I cannot discuss and enumerate them all here. Let the few that follow suffice.

We need to explore the design and performance of perimeter encapsulation systems constructed of alternative materials such as all durable rock, rock over soil, soil cement, and variants of conventional covers over waste. We need to join with the surface water hydrologists and the geomorphologists to refine design procedures for rock toes and aprons that control the potential detrimental effects of headward gully erosion and other geomorphological change. And we need to carry out flume tests to refine design procedures for the transition from the top cover to the sideslope.

I personally do not like basal liner systems that are installed to collect the leachate from the waste. The liner systems demand long-term care to collect and treat the leachate. I believe that the wrong site has been selected if a basal liner system is required to collect the leachate from the waste. The only acceptable site is one where the leachate can continue from the cell to the foundation soils and rocks without detrimental effect. The corollary of this statement is that the base of the cell must meet one or more of the following requirements: a basal layer of geochemically attenuative material must be placed; the foundation soils and rocks themselves must be able to geochemically attenuate the leachate; the evapotranspirative processes at the site must preclude significant downward migration of leachate from the cell; the groundwater must be nonsusceptible to degradation either because of dilative capability or because of preexisting poor quality.

Some of the research opportunities that follow from these statements include: design and performance of long-term geochemical layers; the geochemistry of partially saturated soils and fractured rock systems; rational regulations that do not mandate basal liners but which encourage selection and use of appropriate sites; social systems to deal, in the long term, with leachate from basal collection systems; and the efficacy of wetlands and other natural peatbog-like systems to deal passively with leachate from basal collection systems.

I resist the temptation to discuss and list research opportunities associated with the encapsulated waste. I am sure that there are at least ten research topics for each waste form placed in a disposal cell.

A brief word on the research opportunities open to historians and social scientists in the field of waste encapsulation facilities. I believe that the past twenty years and the next twenty years are a time of immense change and development in the area of waste facility design and construction. The history of what has happened and what is going on is badly documented and poorly understood. I am sure there are many valuable thesis for those who wish to document and elucidate the links between the development of science, social demands for a clean environment, and the legal and engineering practice of waste disposal.

A final word on disposal cells and waste encapsulation facilities as systems: I believe that I must think of them as just that - a complex system. And we must design them and analyze their performance as complex systems. To do this we must understand and use system theory and new ideas in complexity, chaos, chance, and large causes from small beginnings. This will involve contributions from geologists; geomorphologists; geochemists; atmospheric, surface, and groundwater hydrologists; civil, geotechnical, and other engineers; statisticians and complexity theorists; and the natural and social scientists who elucidate the fundamental principles and workings of man, woman, and nature that affect our facilities.

A National Arid Environment Facility

Let me postulate that one of the advantages of national union is the sharing of advantages of resources that are not equally distributed to all states. When cost-effective waste disposal is a national issue, we must recognize that not all states are equally endowed with sites and climates suitable for waste disposal. I recognize the policy imperative in forcing local jurisdictions to take care of the waste they generate; the idea is that local responsibility for waste disposal will lead to a reduction in the generation of waste. Unfortunately this often leads to disposal of waste in areas manifestly unsuited for waste.

Far better to select and use a very small number of sites for all waste. I personally am convinced that an arid environment is a better place for the long-term interment of waste than a wet environment.

If wastes are relocated to a new site in an arid locale, I believe that a viable cell design would involve a long, narrow, and deep trench for the waste. The trench should preferably be excavated into dry soils that are cemented or that possess considerable apparent cohesion due to negative pore pressure.

The cover would be a thick layer (up to 5 m) of soil cement that would arch over the short direction of the trench. In an arid locale, natural evapotranspiration and soil cementing may ensure long-term natural stability of the soil cement and hence of the cover structural integrity. It may be feasible to incorporate low-permeability zones or layers into this arching cover; bentonite or bentonite-amended layers placed as a GCL or conventional soil layer are possibilities. We need to simulate the unsaturated and saturated behavior of this system to establish its performance and the need, if any, for additional low-permeability layers.

In addition we need to study the optimum geometry of the trench for the facility envisaged above. This will involve considerable knowledge about the effect of negative soil pore pressure on the slope stability of the soils into which the trench is excavated. We need to establish both the short and the long-term reliability of negative pore pressures in slope stability. Also the possibility that moisture shed from the soil arch to the "abutments" i.e., the side of the slope, will induce soil softening and cover instability need to be investigated.

Research opportunities associated with this suggestion to establish and operate a national surface or near surface low waste interment facility, include the regulatory implications of national action, the social aspects of the acceptability of such a facility, the economic advantages and disadvantages of one versus many waste disposal facilities, and the many technical and engineering issues associated with the design, construction, and long-term maintenance of such a facility. Technical and engineering research includes issues in long-term geomorphology, seismicity, groundwater, material selection and behavior, trench geometry, surface water control, climate change, and the longevity of various waste toxicity.

Many Site-Specific Cells

The alternative to a national single arid area disposal facility is a series of cells, one for each site. I was at dinner one evening with a friend who proposed this startling idea: federal budgets are being slashed; the DOE's budget is falling rapidly; but we still have many sites and much contaminated material to clean up and dispose of; in short, we do not have enough money to demolish all the old radioactively contaminated buildings and clean the debris; but the risk remains. One way to solve the problem is to build on each site a disposal cell, place into it all the contaminated building and soil waste, and then commit to perpetual leachate collection and treatment.

This would undoubtedly be the lowest capital cost way to reduce current risks. In the long term the operating cost would be higher than for one cell that contains clean, or at least decontaminated waste. But the long-term dose and risk to the postulated receptor may be significant in the absence of institutional controls. I wish that somebody could develop this idea and explore in detail the advantages, disadvantages, and implications of implementing a simple but radical suggestion.

National Programs for Surveillance and Maintenance

Considerable experience with the UMTRA covers suggests that vegetation will grow regardless of the site location, and regardless of the presence of design components intended to eliminate the natural establishment of vegetation. This leads us to the conclusion that it is the responsibility of the designer to provide those components that are know to hinder if not entirely eliminate vegetation growth. But society must accept that long-term maintenance, albeit minimal, will always be required. The U.S. Department of Energy has established a group in Grand Junction, Colorado to do this for both the UMTRA cells and those uranium mill tailings pile now being remediated by their private sector owners. I suspect that in the longer term, this group will have to act as a national center for custodial care and maintenance of many more, and a much wider range of, radioactive and hazardous disposal cells located in all parts of the U.S.

Corporate Liability

If the design criterion is that the cover last for at least 1,000 years, then is there potential corporate liability for that long, assuming that the company designing and building the facility lasts that long. I know of no corporate entity that has been around for 1,000 years, but it is nice to think that in a world of peace and sanity, companies could endure for that long. Certain religious institutions have, for example, lasted a great deal longer than 1,000 years.

In a more practical vein, I suspect we will see a rash of corporate liability suits about 25 to 30 years from now. The immediate argument will be whether the company correctly designed and built to cover to last a mere 30 years, or whether they should have designed and built the cover to be self sustaining and intact after the 30-year maintenance period.

The issue that most worries the corporate lawyer is the design and construction of a cover that by regulation must last at least 100 years. Many companies now in successful practice have a good chance of continuing prosperously for the next 100 years.

These questions may be trivial and [illegible] multidisciplinary study that weaves together social policy, law, corporate practice, and environmental protection.

A National Information Clearing House

I must record and pay tribute to the many people and organizations in the west who working on the issues of long-term covers for radioactive, hazardous, toxic, and municipal wastes. These include but by no means are confined to the Department of Energy and its staff and contractors on the UMTRA Project, at Sandia National Laboratories, Los Alamos, and Hanford. Private industry responsible for the remediation of up to 25 active uranium mill tailings piles is struggling with the issues I raise here. The Department of Defense, faced with base closures in many western states, is building and will have to build many covers. Municipalities have many landfills that are now full and must be covered; and municipal resources are severely constrained, all over the west. I have not quoted any case histories that involve mines in the west, but we must recognize the existence of many mines, and their tailings impoundments, waste rock dumps, sludge ponds, and heap leach pads that will have to be covered in the future.

There is currently no clearing house for the fine work done by these people and their organizations. There is no central focus for technical, engineering, social, or regulatory knowledge accruing to those working in this field. And certainly there is no central research group with the requisite multidisciplinary skills to provide the impetus that is needed for the future.

present is about $50 million. I know that many of my friends and colleagues are responsible for cover projects where the sums of money involved far exceed that. I have no objective way of establishing the total dollars spent and to be spent on covers, but I venture to suggest that if only one percent were spent on focused research and development, the payback to the taxpayer would be immense. I urge others to quantify the cost benefits.

Municipal Landfills

I have not specifically addressed municipal landfills in this paper. I fear that the next wave of attention will have to be on the issue of the long-term performance of such landfills. I believe that most owners, designers, and regulators concentrate on the 30-year design life and perspective for municipal landfills. The contents of most landfills will remain noxious for much longer than this. We will yet have to address such questions as: who will take care of old, closed landfills in the long term; where will the money come from for this care; how will the average landfill behave and perform in the long term if left unattended; what will happen to groundwater when the double liners fail as they inevitably will; how do we minimize total life cycle cost of landfill design, construction, and operation of landfills. I suspect there are other questions I have not considered. Here is challenge enough for the young and vigorous.

CONCLUSIONS AND RECOMMENDATIONS

In this paper I have described an array of covers for remediating sites and for encapsulating wastes that are radioactive, hazardous, or toxic. I have attempted to show that the regulatory regime of the site or project is generally irrelevant to what is required and what is done in order to encapsulate the waste, hinder intrusion to the waste, prevent inadvertent waste dispersal, control infiltration and radon flux, and limit distress and damage of the cell by extreme natural forces.

The primary factors that dictate the design of the cover for wastes must be the nature of the site; the characteristics of the waste; the availability of suitable construction materials; and above all the need to protect human health and the environment for as long a practical and possible. In translating these desiderata into real-world design criteria and technical and engineering approaches I have set out what I believe are the necessary and appropriate norms for any and all radioactive and hazardous waste disposal cells.

I have tried to list the issues that I face as a consultant and design engineer. These issues offer many research and development opportunities to the academic and to industry. I hope only that what I have written here provides the stimulus to others to advance the state of the art, and to save industry and the taxpayer large sums of money.

References

I have used none, so I provide none. I wrote this paper from my head and without reference to notes or reports. To add in a list of papers and books here would be to leave out many, and would focus on those to which I am partial. I see no point or value in that. Call me at (818) 568-7199 if you seek further reading matter on a particular topic.