

REMEDY SELECTION FOR CLEANUP OF UNCONTROLLED WASTE SITES

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ABSTRACT: Selection of remedy for uncontrolled hazardous waste sites involves comparisons of various technological approaches for minimization of threats and achievement of cleanup action levels. Approaches specified in the Comprehensive Environmental Response, Compensation and Liability Act (SUPERFUND Law) National Contingency Plan (40 CFR 300) are broadly labeled as actions, alternatives, and technologies. We have found considerable perplexity in denoting the rank-hierarchy of these approaches and have developed a classification system for dealing with the totality of available measures for consideration in selection of remedy.

SYNOPSIS OF SELECTION-OF-REMEDY PROCESS

Selection of remedy occurs as the culmination of the feasibility study (FS) mandated by provisions (not regulations as such) of the Comprehensive Environmental Response, Compensation and Liability Act [CERCLA (SUPERFUND Law)] of 1980 and 1986. The source document is the yearly revision of the CERCLA National Contingency Plan (NCP) (40 CFR 300). Generally speaking, American site remediation follows the NCP provisions and informally applies to cleanup under such programs of Resource Conservation and Recovery Act (RCRA) Corrective Action, Voluntary Cleanup, and the U.S. Environmental Protection Agency (EPA) Brownfields initiative.

GEOENVIRONMENTAL HISTORY

American remedy selection represents one of the most thoughtful scientific processes adapted to practical engineering efforts of this century. Passage of the Federal RCRA of 1976 focused attention on development of a wide-ranging program of identification of site of generation, management, and disposal of industrial wastes. With this act came definition of what constitutes a "hazardous waste," a term first recognized and adopted by the State of North Carolina in 1952.

What basically became of the RCRA was the further recognition that all of the then-present hazardous waste sites were neither known nor were they manageable in a sense of their ultimate restoration, where hazardous wastes had been spilled, leaked, or dumped into the environment. A new class of environmental threats quickly arose and became known as "uncontrolled hazardous waste sites" (UHWSs). Many of these also became apparent as being orphaned or without identifiable responsible corporate entities or other owning organizations to which governmental entities could look for financial resources to undertake the site restoration process.

Hence the need for the SUPERFUND law (CERCLA of 1980 and its amendment, the SUPERFUND Amendment and Reauthorization ACT of 1986). SUPERFUND, because of the important role of protection of the accused in American law, became a burdensome means by which sites came to be re-

mediated. The act has become the cause of intense bickering between the Congress and subsequent administrations. Since 1995 it has been left unauthorized but is being operated on an individual appropriations basis while the "better way" is sought for the next amending law. CERCLA also serves as a national clearinghouse of UHWSs through its CERCLA List (CERCLIS). CERCLIS entries are made for each and every UHWS candidate or proven "dump" or spill site. Even when investigated and found not to be the location of hazardous substances, the candidate site remains on CERCLIS so that it will not be rediscovered in the future, causing another interpretation of possible environmental threat.

State "Minifunds"

Voluntary Cleanup Programs (VCPs)

Beginning in 1989, the state of Michigan found it necessary to constitute a new form of UHWS remediation. This has become known generally as the VCP, and since about 1995 this alternative has become very popular with state environmental agencies.

VCP has a distinct purpose, which is addressing UHWSs that are either not on the CERCLA NPL or state minifund lists or that have been discovered outside of the RCRA permitting process. In both cases, the essential new ingredient is that some responsible entity has appeared, with requisite funding, and wishes only to conduct the remediation and to put the site to some new land use. Hence VCP sits between RCRA and CERCLA.

"Brownfields" Initiative

A fourth variant is that of the Federal EPA Brownfields program that addresses derelict land in urban settings and for which Federal monies have been made available for competitive grants. These are limited to \$200,000 designed to serve as seed money for state legislatively granted assistance to selected private-sector developers, who are granted often-huge tax relief.

Like the Brownfields initiative, the overall goal of VCP is site redevelopment and also, in general, to create jobs in areas of former urban blight and to assist in the rebuilding of the nation's cities and their sagging infrastructure. In this manner, EPA escapes the burden of doing more with less and passes the funding responsibility to the cities, which look to the legislatures, all outside of long-term or truly substantial help from the Federal government.

RBCA or "Rebecca"

RBCA, or Rebecca, came seemingly from nowhere in 1994, when ASTM released its "Emergency Standard" E-38 (Emergency Standard for RBCA Applied at Petroleum Release Sites). The driving force was EPA's October 31, 1994, release

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that >270,000 leaking underground storage tank (LUST) sites had been reported nationwide and that >1,000 newly discovered sites were coming in each week. RBCA hit the remediation effort like a rocket attack and overnight became widely embraced as a one-stop rationale to "quick and dirty" and owner-favorable release from onerous deliberative selection of action levels. With EPA predicting 400,000 new LUST cases over the next several years, ASTM's Rebecca process was quickly embraced by responsible parties (owners). From this seemingly innocent acceptance has come a potential for "stretching" the process toward inappropriate selections of remedy. What was originally a tool to assist in the handling of low toxicity, highly biodegradable petroleum hydrocarbons, became a tool for highly questionable application to an endless and growing number of completely different chemical compounds.

ASTM's move from laboratory-based standards into the realm of specifying what traditionally has been known as best engineering judgment has been received by engineers as an unwarranted move on their areas of responsibility, as based on formal education and accumulated career experience.

By 1996, ASTM had aggressively released its E-1739 standard for RBCA at petroleum release sites along with an endorsed, private-sector computer simulation of reality, for the so-called Tier 2 site-specific computation of risk. This was accompanied by a training package and computer software to further extend the degree of speculative guesswork concerning site-specific action levels that would extend beyond the simple "look-up" reference tables of Tier 1. In other words, if you do not want to adhere to the more conservative lower action levels (and, therefore, more expensive remediation) you have the option of purchasing the calculational routine to assist your efforts to drive the action level upward to your own level of expectation. Again, the reality of specialized engineering and scientific training, along with appropriate experience are not required. This is a case of "read the guidebooks and select your own action level."

With the unwarranted expansion beyond technical knowledge and real experience came the associated expansion, by one software vendor, to a suite of 80 ground-water contaminants; with this event, the bridge from simple petroleum hydrocarbon fuels to the universe of contamination was complete.

In a short 2 years, RBCA as a system had been retrofit by other interests not necessarily associated with ASTM to an expandable chemical/toxicological database with which users have taken the opportunity to apply it in a blanket sense to any contaminant situation. The database, of course, was set up so that the user could add more laboratory-based single-contaminant characteristics, directly from whatever existing chemical reference handbooks are available.

In 1995, intense industrial site remediation lobbying induced the Illinois legislature to specify that the Illinois Environmental Protection Agency (IEPA) must consider ASTM's RBCA as a suitable means of selection of cleanup action levels for virtually all sites of uncontrolled chemical contamination. With that 1995 stroke of the Illinois legislature, RBCA became the great hope of those interested mainly in the expediency of environmental remediation. Certain special interest lobbyists led to the legislature's order that the IEPA develop rule making for RBCA through the IEPA Tiered Assessment of Cleanup Options. Supporters of the use of RBCA now totally forgot its simple single-contaminant, petroleum-hydrocarbon origin. With the independent vendor computer package came the false rationale of doing away with the basic environmental protection obligation of characterizing both site and waste. The computer package presents three general user requirements (having \$495 to spend, sufficient literacy to read basic operational in-

structions, and the ability to boot-up a computer routine). With these simple requirements, vendors have made unthinking remediation experts of the general population.

As with many expert systems, this one is potentially dangerous, as marketed to nonengineers, substituting computer-based simulations for knowledge, thought, and experience. Field activity can now be avoided to the extent desired by the user, either out of design or from ignorance.

COMMON PATHWAY FOR SELECTION OF REMEDY

SUPERFUND reached its common pathway in 1982, with the release of the first CERCLA National Contingency Plan (NCP), which became the guidelines by which individual sites are studied and subjected to the process of selection of remedy. This situation makes CERCLA a unique law, for it has no regulations as such and operates under the provisions of the NCP.

U.S. EPA found prosecution of CERCLA of 1980 quite difficult without the specific regulations, which this legislation did not require. The original NCP was revised in 1983 and on subsequent occasions to make necessary clarifications. Though most of the changes to the process have been rudimentary, there nevertheless have been grounds for legal arguments relating to the requirements in place at various times. It is common to refer to the version of the NCP that was current at the time formal regulatory action was generated by the applicable Federal EPA region or the state, which may have spoken for the role of state lead.

SEQUENTIAL ELEMENTS OF SELECTION PROCESS

Common sense tells us that hazardous wastes (under RCRA) or hazardous substances (under CERCLA) that "have come to be disposed" on or in the geologic environment must be located, identified, and have their three-dimensional boundaries determined to establish the basis for all subsequent deliberations relating to site cleanup. Successful understanding of this requirement includes recognition that in the interpretation of site history lies the truths of the natural and three-dimensional subsurface position of the threatening hazardous elements and compounds and the natural geologic condition that govern their "fate and transport" to present and future receptors.

Site Characterization

A site must be characterized to identify the possible release conditions from individual source areas as well as the pathways of contaminant transport that may apply to different contaminant groups. It is important to include in site characterization the requirement to identify the nature, position, thickness, structural integrity, and lateral extent of the geologic units underlying the site. The average American has a considerable ingrained resistance to deal with history on a basis of personal understanding and therefore the corresponding "site characterization" is often flawed simply by not knowing where to look in the sense of previous historic technical industrial activity.

Characterization of historic industrial operations includes consideration of the following factors:

- Nature of operation: Feedstocks, process waters and residuals, by gross chemical identity
- Size of plant: How and where did it occupy the property, both for manufacturing and for management and/or disposal of its residuals
- Years of operation: Relates to relative amounts and locations of residuals as today's contaminants

- Changes in ownership: Clues to changes in process, flow quantities and fate of contaminants
- Changes in process: Represents advances in technology or in process economics, hence suspected nature of residuals, their relative volumes and relative locations on the site
- Site geology: Considers earth media as hosts for source areas and migrated contamination; indications of relative ease or difficulty of application of candidate remedial technologies and alternatives
- Site topography: Likely to have changed considerably with decades; discovery of such changes leads to delimitation of waste disposal sites and of potential changes in perched water accumulation and of ground-water movement and associated contaminant transport
- Surface drainage conditions: Evidence of alteration form clues to disposal of wastes and their potential migration
- Frequency of improvement of plant: increases in capacity may indicate progressive policies that may have influenced the manner of operation with respect to quantities and fates of industrial wastes
- Historic litigation: Possible direct relationship with management and operational ethics with respect to plant residuals

Waste Characterization

The fundamental purpose is to locate all surficial and subsurface evidence of the presence of elements and compounds considered to be hazardous. The first question we need to ask ourselves in the conduct of waste characterization is what was the nature of the originating industrial process, their production wastes, and the most probable options for managing/disposing of those wastes? Additionally, we must not forget that industrial process wastes and byproducts are predictable through attentive historic chronological study of contaminated sites.

Identification of Contaminants of Concern (COCs)

Inherent in this deliberation is a review of the wastes identified in the characterization, and the selection of COCs, based on identified physical/chemical characteristics and properties by element or chemical group. Many sites have literally dozens or more of these individual chemical threats, all dealing with site history. Over the years it has been both rational and popular to attempt to reduce this COCs list to about six in number, for the obvious reason of streamlining the process.

In application, early in the 1980s, it became apparent that groups such as volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) were nearly always present, as were the heavy metals. Therefore most risk assessments began to include these groups, as based on the actual laboratory-determined indicators of toxicity, and further weighed and judged by estimates of environmental persistence. To this was added estimates of mobility, in the site subsurface environment, based on comparisons of known or estimated age (historic timing) of on-site disposal.

Identification of chemical groups, quantities, state (phase), concentration, toxicity, persistence, and mobility

Chemical Groups. For purposes of remedy, most multi-contaminant sites will require lumping of elements and compounds into groups of similar physical and chemical characteristics. In fact, the following are a number of reasons for thinking broadly enough to associate the various detected contaminant elements and compounds:

- Like compounds behave in grossly similar manners when contrasted with the entire selection of contaminants detected at the site.
- Like compounds will exhibit similar tendencies for sorption or other forms of retention, within each of the media of contamination. These factors will grossly control their release from temporary disposition in the subsurface.
- Like compounds may tend to coexist to degrees of miscibility in similar media of contamination.
- Like compounds will respond to or reject attempts to apply the various technologies of remediation to relatively similar degrees.

In other words, when we face multigroup contaminants, the first approximation should aim to identify means to gain access to capture, treat, or detoxify individual elements or compounds. Our candidate remedies must prey on similar degrees of contaminant receptivity to our candidate technologies, as combined into assembled alternatives.

Concentration. In the presence of acceptable and accurate site and waste characterization, it is furthermore rational to presume that measured concentrations will be an approximation of the effort necessary to deal directly or indirectly with the contaminant and also of the amount of energy or activity required to remove, treat, or alter the contamination to the benefit of reduction of toxicity. Sheer volume of contamination relates directly to the time that may be required to capture and remove contamination, hence extending the life of expense associated with active or passive remedial actions. Concentration, when freely released from the source area, also represents the supply-side of the geometric size of the plume-like form of migrating contamination containing the COC.

Viewed from another perspective, if we are tracking the volume of the source area as it is affected by capture of its transported (migrated) component, then it may be possible to re-sample the source area and develop a crude relationship relating to the success of our selected remedy. If we can grossly detect and measure the amount of contamination being removed from the subsurface by means of treatment technologies, then we have a basic correlation with observations of reduced concentration within the source area. To include removal, detoxification, destruction, or detoxification, source area direct treatment often represents the best long-term remediation philosophy for most subsurface contaminants.

Concentration conventions in hazardous waste remediation use parts per thousand, million, billion, and trillion. Table 1 attempts to clarify this convention as it is used to identify

TABLE 1. Concentration Conventions Used in Hazardous Waste Management

Parts per (1)	Convention (2)	Liquid equivalent (%) (3)	Solid equivalent (%) (4)	Applicability (5)
Hundred	Percent	%	%	Certain candidate for product recovery Often high enough concentration to allow recovery of pure product for reuse Minimum threshold for many contaminants such as the inorganics and insoluble compounds
Thousand	ppth	g/L	g/kg	
Million	ppm	mg/L	mg/kg	
Billion	ppb	µg/L	µg/kg	Minimum threshold for many organic compounds, especially VOCs and SVOCs
Trillion	ppt	ng/L	ng/kg	Seldom cited as meaningful threat/or practically achievable

contaminant concentrations. Note that there is little practical difference in the convention for aqueous [surface water and ground water (mg/L)] and solid [soil and sediment (mg/kg)] concentrations, and we will use the parts per convention for both states throughout this article.

Toxicity. Unlike the previous factors, toxicity forces us to deal mainly with the basic degree of threat to the environment or to humans. Toxicity is a factor that primarily influences the selection of action level, rather than selection of remedy.

Toxicity of individual compounds is determined from observed inadvertent health effects on humans as well as the results of laboratory testing of organisms taken to death at 50% of the tested population [usually white rats, freshwater shrimp (*C. dubia daphna*), or the fathead minnow]. From these observations and tests, threshold levels have been identified for many of the common pollutants. The question asked in evaluating the toxicity of a compound is at what concentration level will the compound likely cause detrimental health effects?

Persistence. Persistence is a measure of how long a COC can or will remain undispersed and/or undegraded in its earth medium of disposal. There are several ways to consider persistence in selection of remedy:

- Time to natural breakdown to acceptable levels of concentration in the environment
- Time for biodegradation in the environment, above or below the ground surface
- Time to achieve action levels by way of site remediation activities

The writers believe that SVOCs constitute a broad group of contaminants that are not wholly appreciated for the remedial engineering difficulties represented by their generally higher vapor pressure and their often semiviscous to viscous nature. SVOCs also span the light nonaqueous-phase liquid (LNAPL) to dense nonaqueous-phase liquid (DNAPL) spectrum and often are found to be miscibly coassociated, as is the case of polynuclear aromatic hydrocarbons (PAHs) as residuals of incomplete combustion of coal and other organic fuels. SVOCs, therefore, are a broad group of at least semirecalcitrant nature when it comes to applying various active and passive treatment technologies.

As SVOCs are less mobile in any particular medium of contamination, they require more effort as well as special application of technologies more suited to influencing the interparticle realm. For no other consideration than their viscous nature, we are required to think more toward the intimacy of contact to that broader, say radial, area of influence around source areas.

SVOCs typically do not notably move to, mix or mingle with agents of remedial techniques, such as air sparging, inciting flow gradients, or injected gases or fluids intended to make changes in their mobility or toxicity. Of the standard master groups of chemically based contaminants, the SVOCs typically lend themselves more readily, perhaps out of desperation on our part, to direct physical alternatives such as are based in excavation and in-situ mixing. The available alternatives for remediation of this particular group of contaminants certainly begs for more research and development of innovative technologies.

Miscibility of SVOCs

Miscibility is defined as the phenomena of fluids capable of being mixed together or dissolved into each other at any ratio to produce a homogenous substance. Water and alcohol are said to be miscible liquids, in that they readily mix and dissolve into one another. Water and oil, by contrast, are said to

be immiscible, as they do not combine. Additional information on characteristics of SVOCs is available from the Federal Remediation Technology Roundtable (FRTR) via the Internet at <http://www.frtr.gov>

SVOCs potentially exist in the following four phases:

- Gaseous phase: Contaminants present as vapors in unsaturated zone
- Solid phase: Contaminants adsorbed or partitioned onto the soil or aquifer material in both saturated and unsaturated zones
- Aqueous phase: Contaminants dissolved into water according to their solubility in both the saturated and unsaturated zones
- Immiscible phase: Contaminants present as nonaqueous-phase liquids (NAPLs) in both the saturated and unsaturated zones.

Miscible compounds are extremely soluble in water and the sorption rate is very low. This phenomenon means that these compounds will experience minimal retardation and thus may serve as tracer elements when tracking fuel contamination plumes because they tend to travel at the same rate as ground water. Miscible liquids also affect the subsurface environment in various ways (Brusseau, 1993).

1. When added to water, miscible compounds reduce surface tension. This implies that the utilization of these compounds as cosolvents to reduce the liquid to liquid tension and mobilize particular immiscible compounds may be feasible.
2. Organic miscible compounds may cause shrinkage of clay materials. The addition of miscible compounds to a site with large fractions of clay may alter soil conductivity and enhance fluid flow and contaminant mobilization.
3. Miscible compounds may also cause organic components of soil to swell (depending on the characteristics of the miscible compound and the organic material). The swelling of organic material reduces void space in soil, which leads to a reduction in permeability.

Immiscible contaminants naturally mix sparingly in water. When spilled, the immiscibles begin to move downward through the unsaturated (vadose) zone as a separate phase, creating a system with three fluid phases: air, water, and NAPL, in addition to the soil phase itself. In the absence of an aquitard, NAPLs should be able to continue downward and downgradient, displacing air as it moves through the soil structure under the influence of gravity and against capillary forces. As the NAPL passes downward through the porous medium, some of the NAPL (Suthersan 1997; FRTR at previously mentioned Internet website):

1. Volatilizes into the unsaturated pore spaces, which produces a vapor plume. Even though the degree of volatilization from SVOCs is commonly less than a part per million (much less than for VOCs), this process still occurs.
2. Dissolves into the soil moisture, which causes the contaminant to move with the pore water or ground water. This may occur in either the unsaturated or saturated portions of the subsurface.
3. Remains as NAPLs. DNAPLs will tend to sink to the bottom of surface waters and ground-water aquifers. LNAPLs will float on top of surface water and ground water.
4. Coats the soil-particle matrix. LNAPLs may adhere to the soil through the capillary fringe and may be found on top of perched water in the vadose zone.

The spreading of immiscible liquid on the ground-water surface is a result of capillary forces in the air-water capillary zone that prevents the contaminant mixture from entering the aquifer proper. Also acting to drive contaminant flow is the NAPL density. Presence of pore air and pore water in the porous medium reduces the overall migration velocity of the NAPL. The volume of the unsaturated porous medium affected by a limited quantity of NAPL is limited, because a threshold residual saturation must be exceeded before the NAPL can continue to migrate downward and spread laterally. Additionally, if the NAPL volume is sufficient to reach the ground-water surface, a minimum thickness must accumulate before lateral spreading can occur. It follows, then, that relatively large volumes of NAPL must be introduced into a permeable substratum before the presence of NAPL can be observed at some distance from the source. Immiscible-phase liquid spreading on the ground-water surface will, for the most part, occur in the direction of the ground-water gradient. However, upon reaching the ground-water surface, the NAPL begins to "pancake" and thus spreads in all directions. In the case of a large release, NAPL may be observed at considerable distance upgradient (Suthersan 1997).

Representation of Media of Contamination

Having reviewed the presence of contaminants detected in sampled site earth material, sediment, surface water, and ground water, we have an array of elements and compounds of known adverse health effects on humans. At the same time there has always been both a provision and requirement to determine contamination effects on natural resources, and CERCLA has an infrequently used provision for assessment of trebled damages to natural resources. This provision and concern is generally ignored by the environmental agencies as a practical inconvenience to legally driven site remediation.

Identification of media of contamination is a distinctly requisite and unavoidable philosophical step in site remediation. This is where contamination (waste) and geology blend together as the host for the disposed and/or migrating waste and the place at which receptors are likely to become impacted or from which the wastes are released for impact on receptors.

The standard media of contamination emerged quickly, in the early 1980s, as the result of deliberate and consistent thinking on the part of SUPERFUND remediation teams. The standard media are shown in Table 2.

Each one of these earth media represents the place of residence and potential point-of-release of contamination for hazardous waste contamination. With the exception of air, as a medium, the remainder are influenced by site and regional geologic conditions and further represent the physical material in which the contamination takes up residence or from which it is released. Deliberations as to selection of remedy must take into account the position and nature of these media and their mutual effects on actions proposed to remediate UHWSs.

DNAPLs pose a greater threat than LNAPLs because of their potential to sit at the bottom of the saturated soil (on top of the aquitard or bedrock) and form pools that will allow small amounts of the COSs to continue to dissolve into the saturated zone and contaminant passing ground water (Fig. 1). A worst case event is when the DNAPL will find a geologic "holiday" (stratigraphic gap) and flows through the permeable opening to reach the top-of-rock surface and then to seep into the natural fractures as it pancakes, making it almost impossible to accurately locate.

LNAPLs will typically form a small pool on top of the

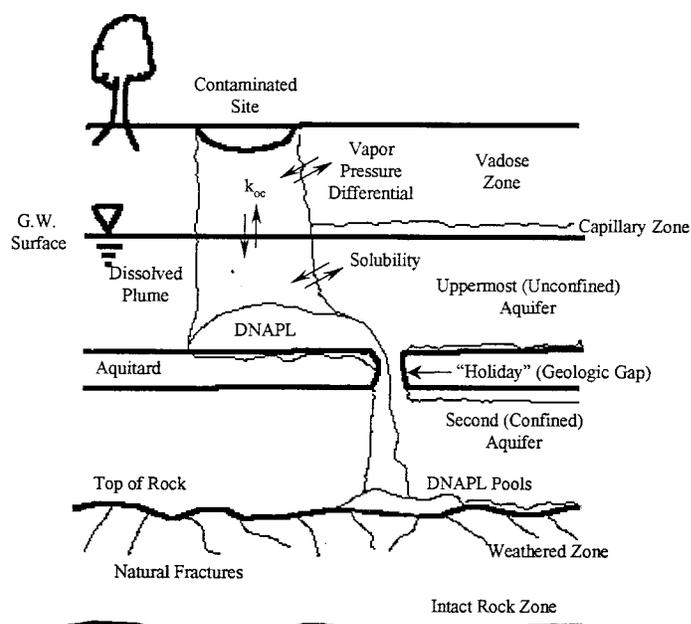


FIG. 1. DNAPLs Migration in Generic Site Cross Section

TABLE 2. Media of Contamination at Uncontrolled Hazardous Waste Sites

Medium (1)	Nature of medium (2)	Impact of medium (3)
Soil	Porous medium capable of storing waste from primary disposal or from migration. Releases vapors in vadose zone or solubilizes to ground water in saturated zone.	When housing wastes from original disposal, known as source area. Capable of continual release unless subjected to direct treatment or removal.
Rock and weak rock	Unusually low-porosity earth material distinguished by its natural fractures.	Capable of receiving, holding and releasing dense nonaqueous-phase contaminants. Never appropriate to dismiss as potential environmental threat.
Sediment	Earth material particles lining streams and ponds. Capable of storing wastes, then releasing such in storm events or during invasive construction.	Represents a constant and indeterminable subsource of wastes for particulate release or ionic desorption to the environment. May have direct secondary impact on food-chain for receptors taking fish and wildlife from body of water.
Surface water	Receives wastes released from bank storage runoff from affected sites. Tends to represent short-period threats based on incoming wastes from source areas; precipitates heavy metal wastes to its sediment.	Common threat to drinking water supplies. Represents a constant and indeterminable subsource of wastes for release to the environment. May have direct secondary impact on food chain for receptors taking fish and wildlife from body of water.
Ground water (to include perched water)	Accumulation of climatic precipitation, infiltrated to depth in earth media and typified by seasonal and temporally variable ground-water surface.	Solubilizes and transports contaminants by gravitationally induced flow from high-to-low topographic areas. Releases contaminants further to environment. Represents valuable natural resource for sustenance of life in foreseeable future.
Air	Does not act to store wastes. Functions as medium of transport and contact for emissions in gas phase.	Carries off waste as emissions received from soil emanations into confined space on the site. Carries waste as emissions during direct treatment of site during remedial actions.

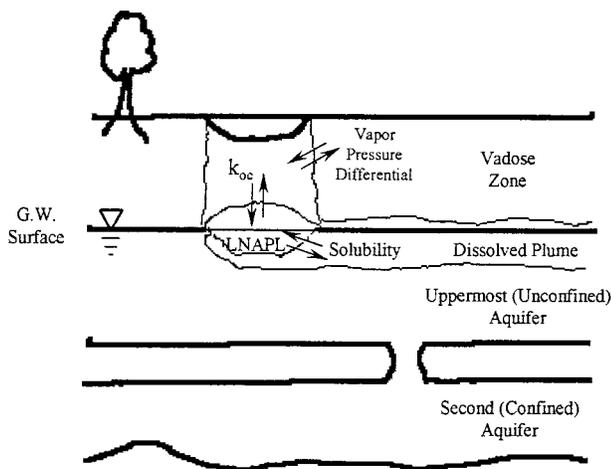


FIG. 2. LNAPLs Migration in Generic Site Cross Section

ground water surface (Fig. 2). Small amounts will dissolve into both the capillary zone and uppermost aquifer (contaminating more soil) based on the COCs' properties but will remain at the top of the aquifer.

Risk Assessment

Simply stated, risk assessment is an attempt to establish a realistic means of appreciation for the most likely scenarios for detrimental exposure to people, the food chain, and environmental resources. Presuming that the characterization team has performed its task to an acceptable level of accuracy, the site remediation process now moves to the step of determination of its relative threat to the environment and to society. This step also represents the second major opportunity to introduce flaws in the remediation system. With the seemingly innocent introduction of RBCA, since about 1995, as a simplifying measure, this single step has emerged as the most controlling state of site remediation.

The original intent of the CERCLA NCP was to rationally determine the negative environmental impact (risk) of site wastes identified in the characterization process. The impact, known as "risk" was the joint effect of the "threat" posed by individual groups and sources of hazardous substances (elements and compounds) as hypothetically coming into contact with a series of "receptors" by way of a chain of events known as the "scenario of exposure." The combined effects of threat and the consequences of the exposure define the risk.

A number of likely scenarios are developed, each based on some societal reason or facet of local life, characterizing how the city or town conducted its affairs. Both present and future land uses are to be included in the deliberations. This activity is complicated, and seldom do two apparently similar sites have more than a gross similarity in the manner in which human and environmental risks are determined for site remediation.

The ultimate goal in risk assessment is to lead the remedy selection team to the action level. It becomes the rationalization for the entire basis of the cleanup effort.

Factors of Risk Further Defined

As the selection of remediation evolves, so does the use and understanding of risk assessment. Given unconstrained resources and the ability to bring together medical, political, economic, and social entities to demonstrate no negative aspects in a future remediation project, one need not be concerned with conducting a risk assessment or the management of risk. However, the criteria stated in the previous sentence are far from reality; risk assessment and management must be

an integral part of a remediation project from inception. There are four major categories we are concerned with when discussing risk:

1. Hazard Identification (which contaminants at the site are we concerned about?)
2. Exposure Assessment (where will the COCs go and which might be exposed?)
3. Toxicity Assessment (how dangerous is the chemical to humans, animals, or the environment?)
4. Risk characterization (estimate the magnitude of risk and its uncertainties)

The literature is rife with varying techniques for quantifying each of these areas. However, no matter how good the science and no matter how correct the methodology, the assessment will not be accepted by those impacted by the potential remediation unless there is effective and convincing communication to both the political and social entities that are influenced by the impact of this remediation process.

Regardless of the science, a basic question must be answered: What is acceptable risk? The answer to this relatively simple question is quite elusive and changes from place to place and audience to audience. The scientist's ability to discuss incremental risk or background risk pales in comparison to being able to provide coherent and believable answers to the following questions:

- What will the solution do to the economy in this location?
- Will people lose their jobs?
- What will happen to my health if you do something/nothing?
- What will happen to my children's health?

The answers your audience may want to hear may quite often be in conflict with each other. Therefore an understanding of the audience you are addressing is quite critical to the development of a remediation technique.

A critical element to the answers to these questions is not the facts in hand but the perception of what is being presented. Identification of a cancer risk of 10^{-6} may not be statistically significant, but it can easily alarm a community. Why? Perception. Regardless of the science involved, the public perception of the risk should be a major concern during the early stages of remediation development.

One approach could make members part of the development of the solution. If a trusted member of the community is an integral part of the development process and the community is convinced this individual has the best interest of the community at hand, then presenting the solution and gaining acceptance may be easier. This is not always the case, and great care must be taken when selecting a member at large from the community—he/she could stall or kill the entire process.

In evaluating those items that affect acceptable risk, there are two major categories:

1. Define the problem and assess the facts.
2. Assess relative values. Address the human element in the decision-making process, and how that decision can impact the quality of life of the community.

Lastly, there is the concept of risk communication. There is a saying that communication is the responsibility of the sender. Failure to properly phrase and transmit our message will ensure it is received in a garbled, misinterpreted manner. As significant amounts of resources are expended on developing a remediation technique, ensure that a public affairs office is

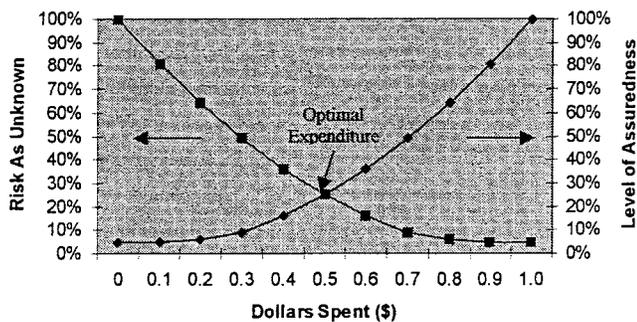


FIG. 3. Risk Accepted versus Site/Waste Characterization Dollars Spent

involved from the beginning and a continuous and credible position is presented from the beginning of the project, not just at the very end. When presenting information ensure you have answers that you also believe in to the following questions:

- Is the presenter listening and acknowledging the concerns of his or her audience?
- Is the presenter capable of handling all the facts of the case—and presenting them in a manner that is understandable to a lay person?
- Can the objectives of the presenter be met and still meet the informational needs of the audience? These two issues can be, and most often are, mutually exclusive.

When assessing, developing, and presenting information on risk it is important to remember that the goal should be to ensure that the needs of the presenter and the needs of the community are mutually inclusive, no exclusive.

Many factors affect the initial risk of a site and waste characterization. As seen in Fig. 3, valuable and important results come from money well spent. Total dollars spent result from several factors that add to the site characterization of a specific site. These factors include sampling and testing to determine location, volume, quantity, and, most importantly, the quality or concentration and species identification of COCs. It is critical to note that when no money (i.e., absolutely no effort) is spent there is 100% risk assumed. Conversely, the amount of risk from unknown or undetected site and waste conditions cannot be driven below ~5% no matter how much money is spent because of uncertainties in site and waste characterization.

Fig. 3 also illustrates a flaw in the sole use of the RBCA approach. The generalities of the program itself make assumptions that a thorough site investigation has been accomplished, while most such efforts are easily contradicted. The RBCA program can, however, be a valuable tool. With the proper input, the output can assist in a proper site and waste characterization allowing the remedial engineer the ability to double check and confirm his initial assumptions, as based on site historical, chronological interpretations, by application of various tests in the field as well as in the laboratory.

One example of this is an improper or not thorough enough site survey that failed to find contamination because of a failure to look long enough or in the right locations based on previous land use of the site. By saving money, the level of assuredness is low and the risk is very high.

Action Levels

Action levels form the basis of the old question how clean is clean? Generally speaking, hazardous waste threats are established by recognition of potential dangers imposed by the presence of the most toxic elements or compounds of each

contaminant chemical group found at the site. Added to this is consideration of the relative concentrations of contaminants from each group. Traditionally, scenarios of contact are developed with a suite of scenarios in which human receptors are placed in likely forms of contact with the waste, by way of ingestion, inhalation, and dermal contact.

Since the inception of RBCA, there is a growing tendency to do away with a broad-based consideration of what may happen in the future if certain aspects of contaminant-based threats are ignored or improperly addressed. CERCLA, for example, is concerned with long-term degradation of natural resources, ranging from water supplies to physical and esthetic aspects of landforms. Under the terms of RBCA, there is a powerful avenue by which the entire matter of waste characterization can skillfully be avoided and by which the nature of potential threats can be downgraded swiftly through the declaration that no one in the site area currently relies on ground water or otherwise contaminated surface water as a source of drinking water. These threats can therefore be ignored, and the site can be closed through the application of no further remedial action planned (NFRAP).

NFRAP, when it is declared at the preliminary assessment stage is itself a callous step away from environmental responsibility because, clearly, not enough is known of site geologic or waste characterization to warrant such a determination. In many cases, even the site investigation (SI) is carried out without sufficient understanding of site industrial history to even plan an adequate subsurface investigation. To make matters worse, some EPA regions have been allowing, since about 1995, the use of less stringent SIs, termed environmental cost estimates, which often are patent excuses conducted for the purpose of showing lack of viable threats to people or the environment.

In the final sense, action levels represent the minimum allowable concentration of each of the COCs to be tolerated as remaining on or below the site at the completion of remedial construction. Most of the time, the action levels selected range from mid-ppb (i.e., 50 ppb or more to low to mid-ppm [i.e., tens to hundreds of parts per million] levels).

Feasibility Study

For sites for which there appears to be a reasonable proven or circumstantial evidence of risk to humans or the environment, a nominal 1-year (respecting the annual hydrogeologic cycle) FS is conducted from about the 6-month point of the remedial investigation. The FS is charged with developing a series of realistic candidate pathways to meet the need to reduce risk from the presence of hazardous substances at the site. When the routine is applied to migrating wastes found at RCRA-permitted facilities, the term is corrective measures study (CMS).

Brainstorming for Candidate Activities

Based on the Site Conceptual Geologic Model, the characteristics of each of the COCs are reviewed with respect to the manner in which they are found dumped or spilled as source areas or migrated contamination in each of the identified media of contamination. The remedial engineering team matches the contaminant group and its media of contamination and then selects as many technologies as possible that are potentially applicable to each of the contaminated media.

During this deliberation, only those technologies seen as capable of creating positive reduction to the COC threat are selected as potential candidates. Technologies should be considered the most specific, most definite, yet fundamental efforts that could possibly be applied to specific COCs, per media of contamination. Another way of appreciating the

TABLE 3. Remediation Screening Matrix^a

Action (1)	Alternative (2)	Technology (3)
(a) Physical in situ		
Containment	Ground-water barrier	Slurry wall
Separation	Solidification and stabilization	Vitrification
Extract (dissolved contaminant)	Desorption (oil-water)	Electrokinetic
Extract (volatile contaminant)	Soil flushing	Water, surfactant
	Vapor extraction	Horizontal/vertical extraction vents
(b) Physical ex situ		
Containment	Surface barriers	Booms berms
Detoxify	Solidification and stabilization	Cement, asphalt
Separation	Degrade (oxidation)	Solar detoxification
	Soil washing	Soil washing
(c) Chemical in situ		
Containment	Solidification and stabilization	Auger/caisson, injector head
Site enhancement	Chemical injection (oxidation/redox)	Injection well
Detoxify	Dehalogenate	Base-catalyzed decomposition, glycolate/alkaline, polyethylene glycol
(d) Chemical ex situ		
Separation	Precipitation	Solvent extraction
	Phase change	Pumping and dry stripping
(e) Thermal in situ		
Extraction (volatile)	Injection	Hot air/steam injection
Destruction	Electrically	Electrical resistance, electromagnetic, fiber optic, radio frequency heating, hot-Hy/Lo pyrolysis
	Desorption	
(f) Thermal ex situ		
Destruction	Incineration	Circulating bed combustor, fluidized bed, infrared combustion, rotary kiln
(g) Biological in situ		
Bioremediation	Landfarming	Landfarming
Aeration	Cometabolism	Phytoremediation, biovent, injection
	Oxygen injection filling	Bioventing, landfarming
(h) Biological ex situ		
Degradation	Aeration	Biopiles, landfarming
	Biodegradation	Fungal/bacterial bioreactor

Note: Technologies have been developed at full scale.

^aThis chart is media nonspecific, the reader determines applicability.

potential match is to think of technologies as being represented by existing equipment that can be ordered via the telephone or modular equipment that can be sized or configured for specific applications in reduction of threat.

Once sight and waste characterization and risk assessment are complete, and action levels have been identified for the contaminants of concern, the next step of the solution is identification of more specific actions that can achieve the remediation objectives. The overriding question is one of methods of remediation. Table 3 lists common actions associated with a generic contaminated site. Each potential action should be listed as a candidate for later screening. Oftentimes, many actions are applicable and should not be discarded too early in the process. This list of actions will be further expanded into alternatives and technologies later and will serve as a starting point to organize the thoughts of the selection team.

Development of Assembled Alternatives

Three primary conceptual strategies are used to remediate most sites:

1. Destruction, detoxification, or phase change of key contaminants
2. Separation of contaminants from the surrounding environmental media
3. Containment of contaminants.

Three main groups of treatment technologies that are ca-

pable of contaminant destruction/detoxification by phase change and subsequent alteration of chemical structure are thermal, biological, and chemical treatment methods. These destruction technologies can be applied in situ or ex situ to contaminated media. Treatment technologies commonly used for separation of contaminants from environmental media include soil treatment by thermal desorption, soil washing, solvent extraction, and soil vapor extraction (SVE) by either phase separation, air stripping, ion exchange, or some combination of these technologies. Selection and integration of technologies should use the most effective contaminant transport mechanisms to arrive at the most effective treatment alternative. For example, more air than water can be moved through soil. Therefore, for a volatile contaminant in soil that is relatively insoluble in water, SVE would be a more efficient separation technology than soil flushing or washing. Immobilization technologies include stabilization, solidification, and containment technologies, such as placement in a secure landfill or construction of slurry walls. None of the immobilization technologies are permanently effective, so that some type of future maintenance will be required.

These concepts of site remediation strategies and representative technologies associated with them are summarized as competing candidates in Table 3. One thing to note is that the choices of applied technologies are not extensive once a strategy is selected. Commonly, no single technology can serve to remediate an entire site or its representative group of contaminants. Several treatment technologies are usually combined at a single site to constitute each of the assembled alternatives.

Rank-Ordering of Candidates in Remedial-Action Hierarchy

Remediation candidates are identified in a three-tiered hierarchy. Viewed from the "top-down," these are actions, assembled alternatives, and technologies. Actions are conceptual, generalized, and lack details. From the top, specificity and detail increases in the downward direction. The selected remedy must, first and foremost, be suited to the COC, then must be able to deliver remediation down to the selected action level and, critically, must be able to achieve the action level within each earth medium experiencing contamination.

In actuality, the identification process begins with brainstorming about potential actions, then jumps to the identification of known or likely technologies. On identification of candidate technologies, a screening process is undertaken to remove candidates in which for some reason (earth media conditions, physical/chemical properties, or waste-disposal conditions) potential success is not likely. Once the surviving technologies have been screen-selected, they are brought together as assembled alternatives. Assembled alternatives are the means by which the overall actions are achieved.

On completion of the array of screened technologies and their assembled alternatives, a second and final comparison screening is conducted, during which the optimal ("best-fit") combinations of alternatives, assembled alternatives and technologies are chosen and recommended to the regional administrator of U.S. EPA, for employment:

1. **Actions:** Actions are loosely defined by 40 CFR 300. They are the broadest level of remedy characterization. Possible actions are containment, removal, separation, extraction, destruction, or bioremediation. They are a conceptual approach to remediation in which the gross nature of contamination is viewed broadly.
2. **Assembled Alternatives:** Groupings of technologies required to meet the objectives of remediation, especially to reach action levels of the COCs; the "assemblage" generally requires more than one technology to isolate, treat, volume-reduce, or remove COCs to the desired action level; seldom are technologies implementable by themselves. 40 CFR 300.430(e)(2) lists several considerations that help drive the selection of alternatives.
3. **Technologies:** The single, most-specific degree of remedial activity in which the subject method is design-specific, product-identifiable, and achievable by the use of either off the shelf tools or those that can be fabricated, installed, and operated for an integrated part of the

remedial process. Think of a technology as being the subject of a telephone call for subcontract assistance or an item procurable from a catalog or list of patented or commonly available equipment.

The manner in which the remedial design options are built is to brainstorm the most likely directions in which the remediation might move, incorporating both equipment and methodologies toward end goals or objectives that are designed to achieve action levels.

As listed earlier, actions encompass the general way in which the site might be remediated to achieve the goals of remediation and to achieve the action levels for each contaminant of concern. With this in mind, we then step to the third level of order, to identify the candidate technologies. Seldom is it possible to reduce or remove the threat of individual COCs with the application of just one technology.

Most COCs, as present in one of the contaminated media, require the associated use of more than one technology to achieve the desired action level. When this is the case, then the applicable technologies, which survive a screening process of identifying how the technology actually can be used, are grouped together, as a number of associated technologies, to form an assembled alternative. Use of the term "alternative" itself identifies that the grouping is considered to be just one of a few pathways to achieve the overall action, which represents a goal or objective in reducing inherent spill or dump site threats.

It has long been said that every UHWS is unique. This fact, however, is often lost on individuals who do not have a strong affinity for site geology or for the basic associations of groups of chemical constituents known as hazardous wastes (under RCRA) or hazardous substances (under CERCLA). The purpose of this paper is to identify some of the lesser-understood elements of the remedy selection process and to deal with them in a forthright manner.

Screening for Selection of Remedy

Remedial actions are made up of the application of assembled alternatives, each consisting of one or more technologies. Remedial design is based on the application of the technologies. Actual remedial objectives are met by selected actions, which themselves are achieved by one or more assembled alternatives.

Screening selection is carried on in the FS as the competing,

TABLE 4. Relative Risk Associated with Selection of Remedy

(1)	Relative environmental risk (2)	Cost (3)	Media (4)	Pitfalls (5)	Remarks (6)
Exhumation	Can be nil	Moderate	Earth sediment	Over-runs not discovered in site/waste characterization	Provides 100% assurance of volume handled
Ground-water control barrier	Low; place in path of known flow	High; one time, very high if in rock or weak rock	Ground water	Requires high QC/QA on emplacement	Passive, once installed; limited to somewhat cohesive host media
Containment	Environmental risk from leaving wastes in place	Low to moderate	All media	Unknown geologic flaws, unknown mobile contaminants	Operates without source treatment, therefore is not final measure
Pump and treat	Low; on basis of observed performance	Moderate to high; may have long-term time over-run	Mainly cohesionless earth media	Unknown aquitard horizons or lenses; sorption or retention of liquid contaminants	Only as effective as site exploration
Bioremediation	Low, if judged by ability to monitor performance	Low; medium depending on species fit to contaminant	Earth and water, above or below ground	Presence of other COCs toxic to degrading organisms	Constantly improving technology, limited by molecular bonds
SVE	Moderate to high	Moderate to high	Mainly cohesionless soils	Depends on microstructure of soil for vapor release	Can be amended by adding more wells

TABLE 5. Site Conditions that May Defeat Accurate Selection of Remedy

Condition (1)	Character (2)	Implication (3)
Lack of consideration of site industrial history leads to ignorance of previous industrial processes, their feedstocks and generic wastes. Characterization therefore neglects key plant areas or components.	Source areas are related to plant locations experiencing spills, leaks and direct disposal as functions of industrial process. Whole periods of industrial usage may be neglected.	Associated contaminants are never discovered and therefore never included in deliberations over risk assessment, selection of action level or selection of remedy and subsequent design.
Historic multi-use industrial manufacturing site.	Multiple plant layout; newer industrial works lie over and obscure older works.	Unanticipated archaeological problem neglects consideration of undiscovered contaminants.
Use of RBCA = "Rebecca."	Often determined on basis of insufficient data such as PA or SI. Many sites are NFRAP'd on totally insufficient basis of knowledge of actual contamination. Method should be applied only to petroleum hydrocarbons.	True nature of contamination is never considered. Site goes to NFRAP on inadequate and erroneous basis.
Lack of discrimination between VOC DNAPLs and SVOC DNAPLs.	SVOC DNAPLs often considered as immobile and therefore of low environmental consequence.	SVOC source areas become unrecognized long-term means of continued contamination of all passing ground water.
Inability to understand and appreciate geologic origin of contaminated sites.	Undiscovered geological physical anomalies may constitute contaminant-transport pathways.	Contamination moves along hydraulic flow vectors not otherwise understood and remains undetected and unremediated.
Lack of appreciation of thinly bedded (layers < 60 cm in thickness) geologic stratigraphy.	Places more hydraulically conductive units in sequences that are falsely-typified as being of lesser hydraulic conductivity.	Contaminant transport reaches depths and down-gradient distribution beyond comprehension of computer modelers.
Failure to develop Site Conceptual Geologic Model.	Site characterization team remains unchallenged to produce an accurate physical model.	Subsequent computer modeling of contaminant transport is inaccurate.
Declaration that glacial lodgment till is too dense and unfractured to pass DNAPL contamination.	Lodgment till typically is broadly fractured with vertical joints able to pass DNAPL contamination.	Underlying ground water may become contaminated to considerable proportions.
Geologic oversimplification of computer-based ground-water flow and contaminant transport models.	May lead to inaccurate understanding of actual state and prognosis of contamination.	Selection of remedy is flawed and may not be protective of environment or populace.

TABLE 6. Generic Contaminant Conditions that May Defeat Meaningful Selection of Remedy

Condition (1)	Character (2)	Implication (3)
Lack of knowledge of contaminants associated with history of industrial processes.	Historic industrial processes no longer in vogue or use.	Associated contaminants are not discovered.
Lack of appreciation of true meaning of "non-aqueous."	"Nonaqueous" is chemist's term indicating only that high solubility is not characteristic.	In reality, solubility of nonaqueous compounds may exceed rational action level.
Use of RBCA = "Rebecca."	Often declared on basis of insufficient data such as PA or SI.	True nature of contamination and transport are never considered.
Lack of discrimination between VOC DNAPLs and SVOC DNAPLs.	SVOC DNAPLs result in being considered as immobile and therefore of low environmental consequence.	SVOC source areas become unrecognized long-term means of continued contamination of all passing ground water.
Mischaracterization of contaminant "plume."	Separate plumes form for each chemical group-related contaminant, or with variable physical/chemical characteristics.	Major plume distribution variances occur between VOCs and SVOCs; latter having significant viscosity in terms of migration in geologic media.

candidate assembled alternatives are reviewed and weighted for the following aspects of relative success:

- **Constructability:** Can the assembled alternative be put in place in each of the site media that have been identified as representing sources or migrated bodies of site wastes?
- **Implementability:** Once in place, can the assembled alternative be made to function to a desirable level of success in reducing or removing the associated COC-specific elemental or compound risk? Table 4 presents relative environmental risks associated with the most common remedial actions.
- **What is the most affordable, yet otherwise reasonably successful, assembled alternative for this specific action?**
- **Time to achieve results:** How long will it likely require to remove or reduce the COC-specific site threat?

As these comparisons are made, the remedial engineering team presents its findings and recommendations to the remediation-oversight agency or the court in which site remediation is being deliberated. An informed decision is then indicated,

based on open discussion and debate, and the process moves to actual remediation design to support construction of remedy. Site closure follows as well as a 30-year period of postconstruction operation and maintenance in which the closed UHWS is judged for the acceptability of its environmental protection performance.

"Screening" is the NCP term denoting the process of identification of potential or candidate forms of remediation and then integrating these technologies into the uniqueness of site and waste characterization. Screening employs the very reasonable concept of best engineering judgment to competitively judge which of the many possibilities constitute the most acceptable means by which a UHWS may be remediated and documented as a site that is believed to require no further remediation.

Selection of remedy is a process that is no better than the accuracy of its underlying site and waste characterization effort. This one factor is at once the most important and the most dangerous facet of site remediation.

Tables 5 and 6 summarize some potential "fatal flaws" in the remedy selection process. A fatal flaw is a condition that,

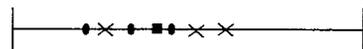
outside of proper engineering, will impede or defeat achievement of a correct solution to the problem. It will cause a situation where the goals of remediation cannot be achieved. Table 5 deals with site conditions, and Table 6 deals with waste conditions that, if undetected, could defeat the remediation efforts.

Managing Uncertainty

The remedial engineering team must take care not to rely too heavily on the use of equations and tabular reference coefficients when developing site geologic and waste characteristics and designing remediation strategies. Empirical equations and reference tables are useful to the remediation engineer as an entry-level, order-of-magnitude estimate of the gross situation only. Design coefficients must be zeroed-in (accurized) with bench-scale laboratory studies and pilot-scale tests to process-model field conditions. Theoretical equations should only serve as a starting point from which to initiate the confirmatory or accurizing lab studies.

The process of validating the design-related calculations generally follows these simple steps:

1. Isolate the contaminants into single COC species, each to represent a particular chemical group, if more than one species is present.
2. List the physical and/or chemical properties that are most likely to govern the process for which the design is being developed.
3. Look up applicable reference values and equations to perform initial "order-of-magnitude" analysis.
4. Make a cartoon sketch (we advise the use of a simple horizontal bar chart) to place competing values and to establish a base for evaluating follow-up test results. Generally, constants can be placed in a band of two log cycles.
5. Consider a simple parametric analysis in which you plug-and-calculate two or more competing coefficients, to judge the general effect of each coefficient on the equation that you have in mind or have just generated.
6. Identify the standard laboratory test (or, alternatively, the test necessary to duplicate the actual contaminant sorption, desorption, release, flow, etc.) that you need to approximate by mathematical computation.
7. Design and fabricate the sample container (if needed) for the contemplated test. Devise a standard procedure if none is available through ASTM, the National Science Foundation, the American National Standards Institute, or other prescribing body.
8. Secure "undisturbed" samples of the COC in the subject earth medium from the actual UHWS.
9. Emplace the contaminant or sample of contaminated media in the test device/holder and do so without disturbing the essential natural geologic fabric of the earth medium.
10. Conduct tests on undisturbed samples and compare to the results from Step 1. Take care to measure the indicated coefficients for reproducibility and under a reasonable range of operating conditions representative of the actual site geologic medium.
11. Plot the values and analyze for data spread. Employ statistical analyses as indicated.
12. Attempt to identify causes of disparity between the two sets of values; reference versus bench-scale laboratory tests. Identify the variance from the reference range. Answer the following question: Are the site samples representative of the entire geologic, hydraulic, and contaminant conditions?
13. Ask yourself what constitutes "conservatism" in terms



- Values from lab studies
- × Values from case studies
- Value from reference tables and calculations

FIG. 4. Managing Uncertainty

of selection of the design coefficient. Are you going to select worst-case, mean, median, medium plus or minus standard deviation? Justify your selection with a written explanation of your logic.

14. Do an extensive case study research to determine what other engineers have determined in similar situations. Based on the findings from this step, it may be necessary to conduct more tests.
15. Make a decision. At this point, the engineer has collected all of the data that would be reasonably expected. Now it is time to manage all of the uncertainties in the data and determine factors of safety to apply to the design. Define the impact of unit steps, involving digits and decimal points, as to what a one-point or one-place shift means in terms of the analytic objective.

These factors of safety represent what may still be unknown or imperfect about the site and waste characterization. They should be applied to calculations that rely on tabulated values about waste characteristics that affect their phase and migration. Fig. 4 graphically depicts the engineer's attempt to manage uncertainty in values used for making decisions.

SUMMARY

Selection of remedy is an open-ended qualitative and semi-quantitative chain of rational discovery and assessment of site and waste factors. Any degree to which the effort is slighted by intentional or unintentional omission of critical site and waste characterization factors degrades the process, often to the point of invalidating the results in terms of human welfare and environmental protection. We must remember that most hazardous wastes/substances at UHWSs were generated by industrial processes of manufacture and distribution and have many historic chronological characteristics. Integration of site geologic (including hydrologic and hydrogeologic) conditions overlays additional controlling or modifying factors. Site remediation efforts conducted in the absence of such technical deliberations are likely to be inappropriate, inaccurate, and/or insufficient.

SPECIAL CONSIDERATIONS

Persistence

One of the basic concerns by which an hazardous waste (under RCRA) or hazardous substance (under CERCLA) is judged in the selection process of COCs is its ability to remain in the environment for long periods of time without degrading or transforming to low toxicity or nontoxic levels. If a compound is judged to be "persistent" then it essentially remains a risk-assessment factor until it can or is either removed or treated, in the sense of remedial engineering. Persistent contaminants typically are the chlorinated (halogenated) compounds or masses of low-solubility unchlorinated compounds, mainly PAHs and also mainly SVOCs.

A new associated term of art is "recalcitrant compound," as promoted by the Battelle Memorial Institute, Columbus, Ohio, a traditional U.S. Department of Energy contractor. Use of the term appears mainly to have served to specifically separate such high toxicity and a highly persistent compounds of

the dioxin, dibenzofuran, and PCB and the pesticide groups but incidentally has been applied on occasion to the PAHs.

There is no design coefficient attached to persistence, merely an unstated caveat that such compounds will resist in some way, all but direct-treatment actions, with the exception of excavation.

Free Product

We use the term "free product" generically to refer to otherwise NAPL compounds that are found in the geologic environment, either in the vadose zone or at or below the ground-water surface. By definition, free product describes a body of liquid-phase contaminant that has remained at essentially its undissolved concentration. The term free product is inaccurate in the general sense of waste characterization for its stems not only from the petroleum industry but carries on the myth that manufactured liquid chemicals have the simplicity of biodegradable total petroleum hydrocarbon that has represented the basic philosophical flaw that RBCA can be expected from the LUST arena and into widespread application for all other groups of potential ground-water contaminants.

One cannot design with the free product concept as it stands only to label bodies of undiluted contamination found either in the original source area or, in the case of DNAPL, at some low-permeability (low in permeability to the contaminant) geologic surface in the saturated zone.

When DNAPLs are not DNAPLs

Remedial engineers working for RPs will want to use the term DNAPL only at the source. The argument here is that as the DNAPL is dissolved into ground water and forms a plume configuration in contaminant transport, then it takes on the character of contaminated water and should be known only as

its generic chemical name, as long as it occupies the vertical space between the source area and lies above an aquitard and in the body of the saturated zone (aquifer). By definition, however, particles of the compound moving on the vertical component of migration and remaining undissolved by passing ground water are DNAPL.

Avoidance of the use of DNAPL as a component of contaminated ground water is driven, of course, by the desire not to have remedial efforts psychologically degraded by lay people who will become confused by this subtle difference and likely will remain at odds against positive activities designed and conducted to remove or lower the DNAPL threat to humans and/or the environment.

ACKNOWLEDGMENTS

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