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RISK ASSESSMENT: HOW SAFE IS SAFE?

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The assessment of risk is a pervasive and complex task. No matter how comprehensive the investigation, significant flaws can be identified due primarily to the complexity of accounting for all components of the environment. Most risk assessments performed address only a subset of the overall environmental risk—human health risk. Even with this enormous simplification, most complexities remain.

Perhaps the most comprehensive broad-range risk modeling tool for assessment of human health risk due to environmental exposures was developed by the United States Environmental Protection Agency (EPA) in 1982. This model, commonly known as the EPA Risk/Cost Policy Model (A.D. Little, Inc. 1979, Booz-Allen et al. 1980) provided the foundation for many human health risk assessment tools, including the indexing tools currently used by EPA regulators.

The EPA Risk/Cost Policy Model systematically compares human health risk and economic cost imposed by different regulatory approaches to hazardous waste management. This policy model, with subsequent enhancements since 1982, has been used by EPA to guide ongoing regulatory impact analyses on current and planned hazardous waste regulations under the Resource Conservation and Recovery Act. While the model has become more sophisticated over the past eight years, the initial concept presented in the Federal Register on December 13, 1982 remains:

> ...the model is designed to assess and compare the costs and risks of different waste management strategies... ...The model will be used as a screening tool to identify those combinations of wastes, environmental settings, and technologies that either pose a greater

> or lesser risk than the majority of combinations. (Federal Register 12/13/82)

EPA is not the only entity interested in developing strategies for hazardous waste management. State and local governments face challenges similar to those faced by EPA in developing hazardous waste regulations. In the private sector, commercial hazardous waste management firms and companies which generate hazardous waste as a by-product of manufacturing operations are faced with the need to develop corporate strategies for managing hazardous wastes. This paper examines the operation of EPA's Risk/Cost Policy Model, and suggests that a similar model be developed and used by the private sector to develop a more cost-effective approach to hazardous waste management. Although presented from the public sector viewpoint, the methodology discussed should be of interest to policy makers in all sectors.

OPERATION OF THE EPA RISK/COST POLICY MODEL

Concept

Previous attempts to develop a "degree-of-hazard" approach for hazardous waste management have been criticized for failing to consider the differences among management practices. As noted by EPA, in the December, 1978 Hazardous Waste Proposed Rulemaking (Booz-Allen et al. 1980), even relatively low-hazard wastes can present a significant risk to human health if managed improperly. The risk/cost policy model was developed to consider not only the hazardous waste characteristics, but the management technology employed and the environmental setting where the practice occurs.

On the basis of these three interrelated elements—the waste, the technology, and the environmental setting—the model assigns risk and cost scores (ICF 1981, ICF 1982). A given hazardous waste may contain several harmful constituents, some more inherently dangerous than others. A particular treatment technology applied to that waste will affect the various constituents differently, rendering some less hazardous and leaving others unchanged (Shelton 1983a, Shelton 1983b, Shelton 1983c).

As the treated waste is transported to an ultimate disposal site and discarded, losses to the environment through the air, groundwater, and surface water may occur; the amount released depends upon the characteristics of the waste (solubility, vapor pressure, concentration, etc. of waste constituents) and the treatment, transport and disposal technology employed (A.D. Little, Inc. 1979, Shelton 1983b). Once released, waste constituents will behave differently depending upon the medium to which they are released and applicable removal and attenuation mechanisms. Finally, the nature of the release's location may make some releases more or less significant in terms of human exposure risk than others (USEPA 1979).

Wastestreams

The risk/cost policy model currently uses a preliminary list of 83 hazardous wastestreams to characterize the types of hazardous waste generated nationwide (ICF 1981, ICF 1982). Each of the 83 wastestreams was defined using average generation rate (kg/day), non-water mass fraction (kg/kg), non-water mass fraction in the form of suspended solids, specific gravity, BTU content, and a list of potentially hazardous constituents. Each potentially hazardous constituent was identified by name, total mass fraction (kg/kg) within the waste, mass fraction (kg/kg) present (dissolved or liquid phase) and physical properties (vapor pressure, solubility, and molecular weight)(ICF 1982, Shelton 1983c).

Treatment Technologies

In addition to the waste characteristics discussed above, each wastestream was assigned a list of feasible treatment technologies. As presently configured, the model (ICF 1981, ICF 1982, Shelton 1983a, Shelton 1983b, Shelton 1983c) includes 21 different treatment technologies. These may be arranged in series; for example, a waste may be treated using chemical precipitation followed by a filter press. By convention, the model accepts up to three treatment "steps" in series, as determined by the user. The 21 treatment technologies are shown in Table 1.

TABLE 1. TREATMENT AND DISPOSAL TECHNOLOGIES

Treatment (Considered Alone or in a Series)

1. Chemical Stabilization/ Fixation
2. Chemical Precipitation
3. Chemical Destruction
4. Chemical Coagulation
5. Filter Press
6. Centrifuge
7. Vacuum Filter
8. Evaporation
9. Air Stripping
10. Steam Stripping
11. Solvent Extraction
12. Leaching
13. Distillation
14. Electrolysis
15. Reverse Osmosis
16. Adsorption
17. Ion Exchange
18. Incineration at 99.99% DRE*
19. Incineration at 99.9% DRE
20. Incineration at 99% DRE
21. Incineration at 90% DRE

* Destruction Removal Efficiency

Disposal Technologies

1. Double-lined Landfill
2. Single-lined Landfill
3. Unlined Landfill
4. Double-lined Surface Impoundment
5. Single-lined Surface Impoundment
6. Unlined Surface Impoundment
7. Land Treatment
8. Deep Well Injection
9. Ocean Disposal

The purposes of treating a hazardous waste are to render the waste less hazardous, to make the cost of subsequent treatment, transportation and disposal less expensive, and/or to recover wastestream constituents for recycle or reuse (ICF 1981, Shelton 1983a, Shelton 1983c). Each of the 21 treatment alternatives available in the model was designed to meet one or more of these purposes, as appropriate for a given wastestream. Each step included a set of computer algorithms which alter the wastestream characteristics; in most cases the algorithms depend heavily on physical and chemical properties of the waste constituents. Where multiple treatment steps are specified, waste effluent conditions from the first treatment step are used as input conditions for the subsequent step in the model.

Cost of Treatment

In addition to altering the hazardous wastestream, each treatment step in the model (ICF 1982) also computes the treatment cost. Costs represent capital and variable direct resource costs only, on the theory that this measure is an accurate reflection of the relative cost of different treatments (ICF 1982, Shelton 1983a). However, use of direct costs does not account for other costs (such as overhead and insurance) which must be paid in the real world. There is also an important distinction to be made between the cost of a service and the price of a service in a commercial context. Price usually includes all costs plus a profit.

Releases from Treatment

The final computation made by the model for each treatment step is an estimate of the quantity of hazardous constituents released from the process (ICF 1982). Releases to each of three media (air, surface water, and groundwater) are computed based upon the nature of the waste constituent (solubility, vapor pressure, molecular weight, and concentration) and the characteristics of the treatment technology (e.g., an open tank process will release more volatile constituents than will a closed process).

Transportation

Once the wastestream has moved through the treatment portion of the model (ICF 1982), it is transported to final disposal. Transportation includes the loading and unloading of the waste from vehicles, as well as the actual movement of the treated waste from one location to another. The EPA model considers three kinds of transport:

- on-site, which includes handling at the generator's site;
- local, which moves the waste off-site a distance of 25 miles; and
- long distance, which moves the waste off-site a distance of 250 miles.

Transportation does not change the physical characteristics of the waste, but imposes additional cost and releases within the model. It is interesting to note that releases attributable to handling the waste (loading and unloading the waste) are larger, on the average, than those caused by accidents in transit for all but the long distance transport (A.D. Little, Inc. 1979).

Disposal Technologies

Nine different disposal scenarios are considered by the model (ICF 1982). These were listed in Table 1. The disposal scenarios are currently undergoing major revisions to reflect the new Land Disposal Regulations and peer review (ICF 1982). The characteristics of the various disposal technologies are specified in some detail, and reflect "typical" scales of operation. In the case of landfills, the model now distinguishes between the typical scale of operation for an on-site landfill (500 metric tons per year) and that for an off-site landfill (60,000 metric tons per year). Direct costs for disposal reflect these typical scales of operation.

For some of the disposal technologies (i.e., landfills and surface impoundments) there are several different scenarios to reflect different levels of regulatory stringency. The unlined landfill and surface impoundment scenarios may be thought of as "worst case" scenarios (Booz-Allen et al. 1980).

Environmental Settings

At this point, the model (ICF 1982) has taken a hazardous wastestream and subjected it to a management technology (including treatment(s), transport, and disposal). The model has accumulated all of the constituent releases and incremental costs associated with the management technology. Now the model is ready to assign specific risk and cost "scores" for using this management technology for this wastestream in each of several environmental settings. The model currently considers 13 different environmental settings, as shown in Table 2. The environment categories reflect differences in local population density, surface water assimilative capacity, and groundwater contamination potential. Also included is a special category for deep ocean waters.

Risk Scores

Risk scores are assigned by taking the Log (Base 10) of the annual release rate for each constituent in each medium, adding a persistence score for the constituent in that medium, adding (or subtracting) an environmental adjustment to account for particularly sensitive or durable environments, and finally adding a toxicity score for the constituent (USEPA 1979). Each score or adjustment added to or subtracted from the Log of the annual release rate, is itself logarithmic. Since the risk score is assigned on a logarithmic scale, the difference between a score of 6 and 7 is a 10-fold increase in risk. Mathematically, the risk score is derived from the classic expression of risk:

TABLE 2. CATEGORIES OF ENVIRONMENTS

Population Density*	Surface Water Assimilative Capacity**	Groundwater Contamination Potential***
High	Low	Low
High	Low	Low
High	High	Low
High	High	Low
Medium	Low	High
Medium	Low	Low
Medium	High	High
Medium	High	Low
Low	Low	High
Low	Low	Low
Low	High	High
Low	High	High
None	Deep Ocean Waters	None

* Population Density: High (520 people/sq kilometer and above); medium (between 52 and 519 people/sq kilometer); and low (fewer than 52 people/sq kilometer).

** Surface Water: Low (flow rate less than 300,000,000 cu m/day or drinking water intake within 6 hrs flow); and high (flow rate more than 300,000,000 cu m/day or lakes with capacity greater than 30,000,000,000 cu m).

*** Groundwater: Low (soil permeability less than 31.5 cm/yr and depth to groundwater saturation zone greater than 10 m; or soil permeability less than 31.5 m/yr and depth to groundwater saturation zone greater than 100 m); and high (all others).

Risk = (Exposure) (Population at Risk) (Probability of Response)

Exposure is a function of the annual release rate and the persistence of the constituent. Population at Risk is determined by the environmental characteristics and persistence of the constituent. The Probability of Response is given by the constituent's inherent toxicity (USEPA 1979).

Cost Scores

Cost scores are determined by converting the sum of all direct costs to a per unit of original wastestream on a dry mass basis (ICF 1982, Shelton 1983a), and taking the log (Base 2). This means that the difference between a cost score of 6 and 7 is a doubling of direct cost. Using a per-unit of original dry mass basis for cost scores assures comparable scores for a given hazardous wastestream.

Current Applications of Model

EPA will use the risk and cost scores to analyze different approaches to regulating hazardous waste management. For example, the model can suggest a list of hazardous waste candidates for banning from landfills. The list, which results from using the model, would require further analysis before any such action; however, the model can be useful in screening wastes initially in this fashion. The EPA Risk/Cost Policy Model is best used generally to address broad policy questions.

It is important to recognize that any use of the risk/cost policy model will require further analysis before regulatory conclusions can be reached. The many simplifying assumptions made in constructing the model must be understood by the user before the implications of any particular model evaluation may be understood. Nevertheless, the model has proven useful in framing issues for further analysis, and in examining general risk-cost tradeoffs between different regulatory strategies (ICF 1981, ICF 1982, Shelton 1983b).

DEVELOPMENT OF A RISK/COST MODEL FOR PRIVATE SECTOR USES

Several assumptions which form the basis for the EPA Risk/Cost Policy Model are not appropriate to assist private decision making. For example, the model uses only direct resource costs as a cost measurement of using different technologies. If the generator wishes to use a commercial waste management facility, the waste generator must consider the commercial firm's price (including profit) in comparison to internal fixed and variable costs for in-house treatment.

Some technologies considered by the EPA model are not available to private waste generators. In particular, the "worst case" landfill and surface impoundment scenarios are not legally available to the waste generator for its untreated wastes (Federal Register 12/13/82, Federal Register 5/19/80).

Some may contend that private decision makers will be guided by only the cost portion of the risk/cost model. It probably is true that over the short term, the cost score alone would reflect the relative total cost of using a particular technology. However, over the longer term, the risk score could serve as a rough indicator of the relative amount of financial liability to which a fire might be exposed as a result of a particular hazardous waste management practice. In light of the apparent trend toward imposing strict liability upon generators of hazardous wastes found at uncontrolled disposal sites (A.D. Little, Inc. 1979), decision makers in the private sector might welcome such a measure of risk.

If a waste generator elects to dispose of waste on-site, it will be required to obtain insurance coverage for potential long-term environmental impairment caused by its facility. The premium to be charged for such insurance coverage will reflect the relative risk of the facility, as measured by a risk assessment performed by the insurance company. The risk scores generated by the risk/cost model might assist the generator in estimating the extent of its on-site exposure (ICF 1981, ICF 1982).

The model (ICF 1981, ICF 1982) necessarily generalizes the national hazardous waste management picture. It uses average or typical values for waste characteristics and waste treatment and disposal capacities. EPA has recognized that the risk/cost model is limited by the general nature of input data. The agency discourages site-specific application of the model as it presently exists; its purpose is to assist in narrowing a large number of waste management alternatives for further analysis in support of rule making. Nevertheless, the concept of developing a risk/cost model using a specific set of waste characteristics, available technologies, and environmental settings would be valuable to the private decision maker.

For the purpose of distinguishing this new model from the risk/cost model, the private sector model will be referred to as the Hazardous Waste Management Cost Effectiveness Model, or simply COSTEF. The following section describes how such a COSTEF model might be applied.

HYPOTHETICAL APPLICATION OF COSTEF MODEL

Consider the case of Acme Automobile Corporation. Acme has six manufacturing facilities in the eastern United States, one each near towns named Amity, Stepford, Salem, Sleepy Hollow, Transylvania, and Metropolis. Acme's new Vice President for Environmental Affairs has been requested to develop a corporate strategy for managing hazardous wastes generated by the company.

Hypothetical Wastes and Treatment Technologies

The Vice President has prepared a detailed inventory (shown in Table 3) of hazardous wastes generated at each Acme plant. The Vice President wants to prepare a cost-effective strategy consistent with company legal and moral obligations to prevent damage to the public health and environment.

TABLE 3. INVENTORY OF HAZARDOUS WASTES GENERATED BY ACME

1. <u>Metal Finishing Wastes</u> (suspended solids = 0.1% by weight), containing 0.037% Hexavalent Chromium and 0.0043% Cyanide by weight. Generated at the average rate of 110 kg/day (Amity), 400 kg/day (Sleepy Hollow), and 550 kg/day (Metropolis). Feasible treatment chains include:
   - Electrolysis and Chemical Coagulation.
   - Chemical Destruction and Chemical Coagulation.
   - Electrolysis, Chemical Coagulation, and Chemical Stabilization/Fixation.
   - Chemical Destruction, Chemical Coagulation, and Chemical Stabilization/Fixation.
   - No treatment.
2. <u>Cyanide Sludge</u> (suspended solids = 10% by weight), containing 6% (Amity and Sleepy Hollow) and 0.6% (Metropolis) Cyanide by weight. Generated at the average rate of 1750 kg/day (Amity), 750 kg/day (Sleepy Hollow), and 1750 kg/day (Metropolis). Feasible treatment chains include:
   - Chemical Stabilization/Fixation
   - Chemical Destruction
   - No Treatment
3. <u>Spent Solvents</u> (suspended solids = 2% by weight), containing 80% (Amity, Salem, Sleepy Hollow, and Transylvania), 70% (Stepford), and 85% (Metropolis) Trichloroethylene by weight. Generated at the average rate of 0.1 kg/day (Amity and Transylvania), 55 kg/day (Stepford), 25 kg/day (Salem), 100 kg/day (Sleepy Hollow), and 115 kg/day (Metropolis). Feasible treatment chains include:
   - Distillation.
   - Incineration at 99.99% Destruction/Removal Efficiency ("DRE").
   - Incineration at 99.9% DRE.
   - Incineration at 99% DRE.
   - Incineration at 90% DRE.
   - No treatment.

The waste inventory will be used as the basic input to the COSTEF model. For each wastestream, feasible combinations of treatment steps have been identified. The Vice President has asked one of his environmental engineers to roughly estimate the direct cost of using these treatment technologies, and to develop treatment algorithms for each. He realizes that treatment may render some of his hazardous wastestreams non-hazardous, and thus use of treatment could form the basis for de-listing wastestreams. Since it appears at least possible that some of Acme's waste could be de-listed (Federal Register 12/13/82, Federal Register 5/19/80) after treatment, the Vice President decides to include unlined disposal scenarios in the COSTEF model.

Hypothetical Environmental Settings

Using common sense, some general surface and groundwater hydrologic data, and 1980 U.S. Census data, the Vice President roughly categorizes the environmental settings for each Acme plan as follows:

Amity:	Medium Population Density, High Surface Water Assimilation Capacity, High Groundwater Contamination Potential
Stepford:	Low Population Density, Low Surface Water Assimilation Capacity, High Groundwater Contamination Potential
Salem:	High Population Density, High Surface Water Assimilation Capacity, High Groundwater Contamination Potential
Sleepy Hollow:	Low Population Density, Low Surface Water Assimilation Capacity, Low Groundwater Contamination Potential
Transylvania:	Medium Population Density, Low Surface Water Assimilation Capacity, Low Surface Water Assimilation Capacity, Low Groundwater Contamination Potential.

Amity, Stepford and Salem are within 25 miles of one another, and Sleepy Hollow, Transylvania and Metropolis are within 25 miles of one another. The Salem metropolitan area is some 250 miles from Metropolis. Commercial hazardous waste landfills are located near both Sleepy Hollow and Stepford (each quote Acme a price of $40 per metric ton for its waste). Using these assumptions, Acme is able to develop and operate the COSTEF model.

Hypothetical Objective Function

Output from this application of the COSTEF model includes some 3,042 different hazardous waste management practices for Acme's various waste-technology-environment combinations. The model output shows that Cost Scores vary from a low of 2.5 to a high of 18.0; Risk Scores vary from a low of 1.8 to a high 10.1. Acme's Vice President, after reviewing the rough output, formulates an objective function which combines cost and risk scores into a single measure of cost effectiveness:

$$\text{COSTEF} = (\text{Cost Score})^2 + (2 \text{ X Risk Score})^2$$

The lower the value of COSTEF, the better. Using this measure of cost effectiveness, Table 4 was prepared to show the most cost-effective and least cost-effective hazardous waste management practices for each wastestream generated by Acme.

Discussion of COSTEF Model Results

Each management practice shown in Table 4 would be a suitable subject for a paper. Much additional analysis of the results shown would be required before any hazardous waste management strategy could be adopted by Acme. These caveats aside, the model output is nevertheless interesting.

The first waste management practice shown for the Amity plant—that of on-site deep well injection of metal finishing wastes—is useful to demonstrate the kinds of further analysis required to use model results. Deep well injection is heavily dependent on the nature of site geology; a detailed site investigation would be required before the

TABLE 4. SUMMARY OF COSTEF MODEL RESULTS

Amity Plant

Most cost-effective waste practices

1. Metal Finishing Waste (110 kg/day): dispose to on-site deep well without pre-treatment; Cost Score = 10.0, Risk Score = 4.7, COSTEF = 13.7.
2. Cyanide Sludge (1750 kg/day): treat with Chemical Destruction and transport to commercial double-lined landfill in Stepford; Cost Score = 10.2, Risk Score = 3.5, COSTEF = 12.4.
3. Spent Solvent (0.1 kg/day): transport to either Salem or Stepford for distillation, residue to unlined surface impoundment; Cost Score = 2.9, Risk Score = 2.5, COSTEF = 5.8.

Least cost-effective waste management practices

1. Metal Finishing Waste (110 kg/day): dispose to on-site, unlined landfill without pre-treatment; Cost Score = 15.4, Risk Score = 7.7, COSTEF = 21.8.
2. Cyanide Sludge (1750 kg/day): dispose to on-site, double-lined landfill after chemical stabilization/fixation; Cost Score = 13.6, Risk Score = 6.3, COSTEF =18.5.
3. Spent Solvent (0.1 kg/day): incinerate to 99.9% DRE and dispose of residuals to on-site, double-lined landfill; Cost Score = 16.9, Risk Score = 4.5, COSTEF = 19.1.

Stepford Plant

Most cost-effective waste management practice

1. Spent Solvent (55 kg/day): burn on-site to at least 99% DRE; Cost Score = 7.7, Risk Score = 3.8, COSTEF = 10.8.

Least cost-effective waste management practice

1. Spent Solvent (55 kg/day): burn on-site to 99.99% DRE, with residuals to on-site, double-lined landfill; Cost Score = 16.5, Risk Score = 3.7, COSTEF = 18.1.

Salem Plant

Most cost-effective waste management practice

1. Spent Solvent (25 kg/day): distillation, with residue to unlined surface impoundment at Amity or Stepford; Cost Score = 3.2, Risk Score = 5.9, COSTEF =12.2.

Least cost-effective waste management practice

1. Spent Solvent (25 kg/day): incineration to 99.99% DRE, with residue to on-site, double-lined landfill; Cost Score = 16.9, Risk Score = 5.6, COSTEF = 20.3.

TABLE 4. (cont.)

Sleepy Hollow Plant

Most cost-effectiveness waste management practices

1. Metal Finishing Wastes (400 kg/day): transport untreated to unlined surface impoundment in either Transylvania or Metropolis, or to deep ocean waters for disposal; Cost Score = 11.1, Risk Score = 5.3, COSTEF = 15.3.
2. Cyanide Sludge (750 kg/day): transport untreated to unlined surface impoundment in either Transylvania or Metropolis, or to deep ocean waters for disposal; Cost Score = 7.7, Risk Score = 3.3, COSTEF = 10.1.
3. Spent Solvent (100 kg/day): burn on-site to at least 99% DRE; Cost Score = 6.6, Risk Score = 4.1, COSTEF = 10.5.

Least cost-effective waste management practices

1. Metal Finishing Wastes (400 kg/day): electrolysis followed by chemical coagulation followed by long distance transport to deep ocean waters for disposal; Cost Score = 18.0, Risk Score = 8.4, COSTEF = 24.6.
2. Cyanide Sludge (750 kg/day): chemical stabilization/fixation followed by on-site disposal to double-lined landfill; Cost Score = 13.6, Risk Score = 5.9, COSTEF = 18.0.
3. Spent Solvent (100 kg/day): incineration to 99.99% DRE, with residual disposed to on-site, double-lined landfill; Cost Score = 16.9, Risk Score = 4.0, COSTEF = 18.7.

Transylvania Plant

Most cost-effective waste management practice

1. Spent Solvent (0.1 kg/day): burn on-site to at least 99% DRE; Cost Score = 6.6, Risk Score = 2.1, COSTEF = 7.8.

Least cost-effective waste management practice

1. Spent Solvent (0.1 kg/day): incineration to 99.99% DRE, with residual disposed to on-site, double-lined landfill; Cost Score = 16.9, Risk Score = 4.3 COSTEF = 19.0.

TABLE 4. (cont.)

Metropolis Plant

Most cost-effective waste management practices

1. Metal Finishing Wastes (50 kg/day): dispose to on-site deep well with no pre-treatment; Cost Score = 10.0, Risk Score = 5.4, COSTEF = 14.7.
2. Cyanide Sludge (1750 kg/day): treat with chemical destruction, and dispose of residual to commercial double-lined landfill in Sleepy Hollow; Cost Score = 10.2, Risk Score = 3.6, COSTEF = 12.5.
3. Spent Solvent (115 kg/day): distillation, with residual waste to single-lined landfill in either Sleepy Hollow or Transylvania; Cost Score = 3.1, Risk Score = 6.8, COSTEF = 13.9.

Least cost-effective waste management practices

1. Metal Finishing Wastes (50 kg/day): electrolysis followed by chemical coagulation followed by long distance transport to deep ocean waters for disposal; Cost Score = 18.0, Risk Score = 7.5, COSTEF = 23.4.
2. Cyanide Sludge (1750 kg/day): treat with chemical stabilization/fixation followed by long distance transport to deep ocean waters for disposal; Cost Score = 12.3, Risk Score = 7.7, COSTEF 19.7.
3. Spent Solvent (115 kg/day): incineration at 99.99% DRE, with residuals disposed in an on-site, double-lined landfill; Cost Score =16.9, Risk Score = 6.1, COSTEF = 20.8.

feasibility of this practice could be determined. In addition, the nature of this wastestream (a corrosive waste containing 0.1% suspended solids) probably makes the feasibility of deep well injection without pre-treatment doubtful. Further investigation of site suitability and the waste for deep well injection is needed.

The second waste management practice shown—chemical destruction and commercial landfilling of cyanide sludge—demonstrates the apparent cost effectiveness of treatment before disposal. The raw data indicates that commercial landfilling of this waste, untreated, would be slightly less expensive (Cost Score = 9.9 vs. treated Cost Score of 10.2) but much riskier (Risk Score = 5.2 vs. treated Risk Score of 3.5).

The third waste management practice shown—distillation of Amity's spent solvent with residue to unlined surface impoundment in either Stepford or Salem—raises the question of on-site versus off-site waste management. The only difference between the environmental settings of Amity and Salem is that the latter is more densely populated. The suggestion that Amity's waste be transported to Salem for disposal seems at first counterintuitive. The explanation is that the model distributes transportation losses equally between the generation environment and the disposal environment. Spreading these transportation losses between two environments lowers the overall risk, where releases due to transportation are the most significant releases. The assumption underlying this rationale merits closer examination by Acme.

In general, the least cost-effective waste management practices include sophisticated treatment technologies operated in series. A different objective function, or different assumptions regarding chemical constituents, would probably change the recommended waste management practices.

CONCLUSIONS

As noted above, the COSTEF model suggests a beginning of analysis, rather than an end. Use of the model as more than a simple screening device is inappropriate at this stage of development. The model is useful in framing questions regarding the most cost-effective hazardous waste management practices and in providing a systematic means of considering risk and cost tradeoffs between different strategies, final decisions regarding the most appropriate set of hazardous waste management practices—whether at the national, state, local or private level—must continue to be made by human decision makers after careful consideration of all technical legal, economic, and institutional factors. Models such as the one described in this paper can serve only as tools in the decision-making process.

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