Chemical and Nuclear Waste Disposal: Problems and Solutions

James P. Murray, Joseph J. Harrington, and Richard Wilson

I. Introduction

The problems of waste disposal have always been with us. In biblical times, the residents of Jerusalem always burnt their wastes in the hideous Vale of Gehenna. This gave way to burial of waste or sometimes dumping it in shallow oceans. All too often the sewage pipes of the seaside towns did not even take the waste to the low tide mark; and the use of the deep oceans as a disposal site has been almost unknown.

As time has progressed, not only has the number of people increased but the amount of waste per person has increased as well. This has led in the last 10 years to a greater public concern over waste disposal

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problems. But only now is there a willingness to understand and calculate numerically the deleterious health effects, and to be conservative in hazard estimation in the face of uncertainty. As we examine the problems, we note two important changes of perception in the last 100 years.

A hundred years ago it was believed that there was some threshold for harm in exposure to any toxic chemical, and therefore if that chemical were adequately diluted, the potential for harm would disappear. This view faced its first challenge in the 1920s when there was a search for the threshold of exposure to x-rays below which no one would get cancer. No one was able to establish such a threshold. In 1928 the International Commission on Radiological Protection began its work; this commission believes it is prudent to assume that no threshold exists and espouses a proportional dose-response relationship for prudent public policy purposes. Once this has been accepted for radiation-induced carcinogenesis, it is a short logical step to assume that a proportional dose-response relationship might hold as well for chemically induced carcinogenesis. If we assume that a proportional dose-response relationship *might* exist for some hazards we can no longer assume that waste problems are solved by dilution.

Another important issue is our new willingness to calculate and address the health problems we create for subsequent generations. It used to be acceptable to dispose of waste products using methods sufficiently secure that the products would not be exposed to our environment for perhaps 100 years. Now we are beginning to ask, what will happen after the 100 years?

It is the *simultaneous* change of both of these criteria that has changed our perception of the waste issue and has made solutions to the problem complex. The changes are recent enough that no general solution for estimating risk has been propounded; worse still, not only do we not know the solution, the problems have not been well formulated and we have not asked all the relevant questions. In this paper, we outline what we consider to be a reasonable first approach to determining what the problems of hazardous chemical and nuclear waste disposal are and give some tentative answers to some of the relevant questions.

We emphasize that our definition of the problems need not prejudice the solutions. Various moral and ethical considerations, which we as analysts may perceive differently from a decision-maker, will significantly influence decisions. By outlining the problems and issues, and by making comparisons, we hope that expenditures of societal, fiscal, and emotional capital on these problems will achieve the best possible results.

We have found it most instructive to compare hazardous chemical waste disposal problems with the problems of nuclear waste disposal. In section II, we outline and compare the compositions and volumes of hazardous chemical wastes with hazardous nuclear wastes. In section III, we briefly address the current procedures for treating hazardous chemical and nuclear wastes: landfilling; incineration; chemical, biological, and physical treatments; deep-well injection; mined geologic disposal; subseabed disposal; or even abandonment. In section IV, we discuss the fate and persistence of the components of hazardous chemical and nuclear wastes after their disposal. We also summarize the implications of Love Canal—a leaking chemical waste dump near Niagara Falls, N.Y., and of Oklo—a buried natural nuclear reactor in Gabon, West Africa.

In section V, we discuss the problems in estimating risk and present several examples of risk calculations applied to different types of hazardous waste. In section VI, we conclude by summarizing our comparison of hazardous chemical and nuclear waste disposal.

The final aim of the analysis is to combine all this information into a risk assessment—a quantitative assessment of the risk to life and to the environment—and to present it to the decision-maker, politician, environmentalist, or homemaker for their decisions. This has been attempted for nuclear waste, and indications are that the risk could be very small, given proper disposal. Attempts to calculate risk for chemical waste have barely begun.

II. Compositions and Volumes of Wastes

Composition of Hazardous Chemical and Nuclear Waste

One of the difficulties in comparing hazardous chemical and nuclear wastes is knowing what they are. Section 3001, Subtitle C, of the Resource Conservation and Recovery Act of 1976 (RCRA), directs appropriate federal and state agencies to "develop and promulgate criteria for identifying the characteristics of hazardous [chemical] wastes, which should be subject to the provisions of this subtitle, taking into account toxicity [including carcinogenicity], persistence, and degradability in nature, potential for accumulation in tissue and other related factors such as flammability, corrosiveness and other hazardous characteristics."[1] EPA has diligently addressed this issue

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[1] 42 USC 6921, Public Law 94-580, October 21, 1976.

but even so, characterization of the waste is complex and can be quite confusing.

The large number of chemical substances that may be hazardous brings to light some tremendous problems. For example, the National Institute of Occupational Safety and Health (NIOSH) estimates that 86,000 unique chemical products were manufactured by 10,000 companies during the years 1972 to 1974.[2] When one considers the number of elemental compositions or molecular rearrangements possible, the numbers become phenomenally large. The fraction of the chemicals that are now considered hazardous is somewhere around one percent of those in the NIOSH list. This would be approximately 1,000 chemicals, although EPA lists do not yet contain quite this many.[3]

In addition to the hazardous chemical wastes produced by manufacturing and non-manufacturing industries, mining wastes, domestic wastes, oil industry spills, and coal mining and burning wastes also have toxic, hazardous components. A good example is coal.

Coal burning in power plants and processes under design for liquid fuel and gas production produce gaseous emissions such as carbon, sulfur and nitrogen oxides, polycyclic aromatic hydrocarbons, and other toxic substances (arsenic, cadmium, fluoride, mercury, molybdenum, antimony, selenium), as well as radionuclides.[4] Of particular importance is the fact that the radionuclide population doses associated with modern coal-fired power plants appear to be greater than those associated with nuclear power plants having comparable power-generating capacity.[5]

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[2] NIOSH, *National Occupational Health Survey*, vol. 2 (Washington, D.C.: U.S. Government Printing Office, 1977), p. 21.

[3] 45 Federal Register 98, May 19, 1980, p. 33063; 45 Fed. Reg. 138, July 16, 1980, p. 47833; 45 Fed. Reg. 220, November 12, 1980, p. 74884; and 45 Fed. Reg. 229, November 25, 1980, p. 78524.

[4] National Academy of Sciences Committee on Accessory Elements, *Redistribution of Accessory Elements in Mining and Mineral Processing, Part I, Coal and Oil Shale*, 1979.

[5] Estimated emissions from a 1,000 MW_e (megawatts of energy per year) coal-fired power plant with only one percent of the introduced radionuclides released from the stack are: uranium-238 (8×10^{-3}); uranium-235 chain (3.5×10^{-4}); thorium-232 chain (5×10^{-3}); radon-220 (0.4); and radon-222 (0.8) Curies per year. Cf. J. P. McBride, R. E. Moore, J. P. Witherspoon, and R. E. Blanco, "Radiologic Impact of Coal and Nuclear Power Plants," *Science* 202 (1978): 1045.

The weights of the uranium and thorium releases alone are 23.2 kilograms and 46.4 kilograms respectively. Expected health effects from these polluting stack emissions have been discussed earlier. (See R. Wilson, S. D. Colome, J. D. Spengler, and D. G.

Nuclear wastes are an important part of the overall waste disposal problem. Like hazardous chemical wastes, we will limit our discussion to the risks imposed by civilian wastes. Nuclear power plants produce the greatest amounts of civilian high-level radioactive wastes, measured in Curies (Ci) per year. The reactors in use today are principally light water reactors (LWR), either boiling water reactors (BWR) or pressure water reactors (PWR). A high temperature gas-cooled reactor is also being operated at Fort St. Vrain, Colorado.

The Department of Energy has been mandated by law to conduct research on the safe disposal of nuclear wastes and ultimately to provide for their actual disposal in certain cases. The Nuclear Regulatory Commission, meanwhile, has primary responsibility for waste disposal licensing and must decide whether nuclear facilities have the technology to ensure adequate waste disposal.[6]

Nuclear wastes are divided into three categories: high-level wastes (HLW), transuranic wastes (TRU), and low-level wastes (LLW). High-level, commercial nuclear wastes are, for the most part, spent fuel rods from LWR reactors and some fuel processing waste. These fuel rods plus adjacent radiation targets, mostly stainless steel fuel rod encasements and moderating fluids, contain over 99 percent of the radionuclides produced during reactor operation.[7] Fuel rods are currently in wet-pool storage until permanent waste disposal facilities become available.

Transuranic waste is an assemblage of industrial cleanup waste, etc., that is only moderately contaminated with transuranic radionuclides that decay by alpha-particle emission, except for plutonium -238 and plutonium -241, which are considered to be particularly dangerous (fissile). The waste is specified to have greater than 10 nCi (nanocuries) per gram of alpha activity to classify it as a TRU waste.

Low-level wastes include almost any material contaminated by low levels of radionuclides. They are specified to contain less than 10 nCi of actinides per gram. This type of waste is generated by

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Wilson, *Health Effects of Fossil Fuel Burning—Assessment and Mitigation* (Cambridge: Ballinger Publishing Co., 1980). What should be asked, however, is what happens to the other 99 percent?

[6] DOE-NRC, *In the Matter of Proposed Rulemaking on the Storage and Disposal of Nuclear Waste (Waste Confidence Rulemaking) PR-50, 51 (44FR61372) Statement of Position of the United States Department of Energy,* DOE/NE-0007, April 15, 1980.

[7] Oak Ridge National Laboratory-DOE, *Spent Fuel and Waste, Inventories and Projections,* ORO-778, August 1980.

hospitals, government and private research organizations, university laboratories, and commercial nuclear energy operations.

The principal isotopes generated by radioactive decay or activation in reactors and that could represent a serious hazard are: tritium, carbon-14, strontium-90, technetium-99, iodine-129, cesium-135, cesium-137, samarium-151 (?), lead-210, polonium-210, radon-222, radium-226, thorium-229, protactinium-231, uranium-232-238 (?), neptunium-237, plutonium-238-241, americium-241, 243, and curium-244. (The ? indicates that the seriousness of the hazard is debatable.) Uranium mining wastes also appear to pose a significant hazard. For example, in Grand Junction, Colorado, radon-222 gas has diffused from mine tailings that were used in the construction of development housing.[8]

Quantities of Waste Produced

In addition to specification of what types of waste are considered hazardous from a chemical-biological point of view, volumes of the types of waste generated are important because of the volume dependence of total possible ecological or human risk, and the volume dependence of cost for treatment and disposal.

Several research groups have done an extensive amount of work in estimating the total amounts of hazardous chemical waste generated by manufacturing and non-manufacturing industries.[9] EPA's most recent estimate of 1979 "volumes" (weights) is about 60,000 TMT (thousand metric tonnes).[10] For mining wastes, excluding uranium mining waste, somewhere between 442,000 and 1,320,000 TMT

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[8] DOE, *Annual Status Report on the Uranium Mill Tailings*, Remedial Action Program, DOE/NE-0011, December 1980.

[9] Hugh J. Van Noordwyk, "Quantification of Municipal Disposal Methods for Industrially Generated Hazardous Wastes" in David Shultz, ed., *Treatment of Hazardous Waste, Proceedings of the Sixth Annual Research Symposium*, EPA 600/9-80-11, 1980, p. 8; EPA Office of Solid Waste, *RCRA Background Document 1951.3B, Chapter VI, Hazardous Waste Generation, Transportation and Disposal*, 1980, p. 1; D. A. Sharp, et al., Office of Solid Waste, Hazardous Waste Division, *Final Report on Cost of Compliance with Hazardous Waste Management Regulations to U.S. Environmental Protection Agency*, Contract 68-01-4360, Battelle Columbus Laboratories, 1978; Booz-Allen and Hamilton, Inc. and Putnam, Hayes and Bartlett, Inc., *Hazardous Waste Generation and Commercial Hazardous Waste Management Capacity—An Assessment*, SW-894, EPA Office of Water and Waste Management, December 1980; EPA, *State Decision Maker's Guide for Hazardous Waste Management*, SW-612, 1977; S. W. Plehn, Office of Solid Waste, EPA, *Final Environmental Impact Statement, Part 1, for Subtitle C, RCRA of 1976;* and M. Ghasemi, et al., TRW Environmental Engineering Division, *Technical Environmental Impacts of Various Approaches for Regulating Hazardous Waste Generators*, vol. 1, prepared for EPA, Office of Solid Waste, 1979.

[10] 45 Fed. Reg. 98, p. 33063.

of hazardous chemical waste was estimated to be generated in 1975.[11] Other chemical wastes, such as 84,000 TMT of coal ash, 13,000 TMT of cement kiln dust, and materials such as oil tanker spills, brines, drilling muds, the hazardous fraction of domestic household wastes, and an estimated "volume" of one percent of domestic sewage add up to a "maximum-value estimate" of about 400,000 TMT.[12]

Approximately 760,000 generators of manufacturing and non-manufacturing hazardous chemical wastes exist in the United States. About 73.9 percent of these produce less than or equal to 100 kilograms per month and about 91.2 percent produce less than or equal to 1,000 kilograms per month. In terms of the total amounts of waste generated, however, all those that produce less than or equal to 100 kilograms per month generate only about 0.23 percent of the waste; and all those that generate less than or equal to 1,000 kilograms per month generate only about 1.05 percent of the waste.[13] This type of information is what encouraged the EPA to limit regulations to producers of less than or equal to 1,000 kilograms per month. Nonetheless, additional complexities exist in regulation as well.[14]

Nuclear wastes are different. "Volumes" of high-level wastes produced in 1980 were 1.58 TMT of spent fuel rods and 0.45 TMT of nuclear fuel services waste. "Volumes" of transuranic waste were about 1.5 TMT. "Volumes" of low-level wastes are about 49 TMT for fuel cycle wastes and 44 TMT for non-fuel cycle wastes.[15] Uranium mining waste totaled 7,010 TMT for tailings and 142,000 TMT for overburden. "Volumes" for high-to-low-level wastes are calculated from actual data and estimated densities: 10 grams per cubic centimeter for fuel rods and 1 gram per cubic centimeter for others

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[11] PEDCo. Environmental, Inc., *Study of Adverse Effects of Solid Wastes from all Mining Activities on the Environment,* draft for EPA, 1979.

[12] S. Rhodes, *Cost and Quality of Fuels for Electric Utility Plants – 1979,* FPC-423, DOE/EIA-0191(79), VC-97, June 1980; PEDCo, Environmental, Inc., *Adverse Effects;* Council on Environmental Quality, *The Eleventh Annual Report of the Council on Environmental Quality,* 1980; COMRATE, *Mineral Resources and the Environment, Supplementary Report: Resource Recovery from Municipal Solid Wastes,* 1975; EPA, *Fourth Report to Congress, Resource Recovery and Waste Reduction,* SW-600, 1977; and Council on Environmental Quality, et al., *The Global 2000 Report to the President,* vol. 1, 1980.

[13] M. Ghasemi, et al., *Technical Approaches.*

[14] 45 Fed. Reg. 98, p. 33063.

[15] DOE, *Spent Fuel and Waste Inventories and Projections,* ORO-778, UC-70, August 1980. Also personal communication with Dr. K. J. Notz, ORNL; DOE, *Nuclear Waste Management Program Summary Document,* FY 1981, DOE/NE-0008, UC-70, March 1980; and DOE, *Spent Fuel Storage Requirements, An Update of DOE/NE-0002,* DOE/SR-0007, UC-85, March 1981.

(aqueous). Volumes for mining wastes are calculated with published weight data and a density of 1.55 grams per cubic centimeter.

There have been 69 commercial nuclear reactors operating at some time between 1960 and 1980 that generate all levels of nuclear waste.[16] Fred C. Hart Associates, Inc. has estimated that 7,200 hospitals, 3,200 medical laboratories, and 5,700 research facilities produce hazardous wastes.[17] It is likely that a significant fraction of these facilities produce LLW wastes in small amounts. Twenty-five uranium tailings piles also exist.[18]

Actual volumes of hazardous chemical and nuclear wastes are compared in Figure 1. All the cubes to the left of the uranium mining cube represent the total volume estimate of hazardous chemical waste. The question marks at the center of some of the cubes imply that the lower bounds cannot be accurately estimated. It is immediately apparent that the *volumes of hazardous chemical wastes are enormous compared to nuclear wastes.* Moreover, if we ignore the problems associated with mining wastes—these wastes are essentially geometric natural earth rearrangements and can be considered minor hazards—the difference between hazardous chemical and nuclear wastes becomes a several orders of magnitude difference. Hazardous nuclear waste would then be represented by the tiny cubes in the lower right-hand corner of Figure 1 (representing high-level, low-level, and transuranic wastes). Finally, it is interesting to note that if we were to expand the nuclear waste volumes (including uranium mining) by a factor of 10, the size of the cube edges would only increase by a factor of 2.15. The obvious volume differences between the amounts of hazardous chemical and nuclear wastes generated would still exist.

In addition, since there are a much larger number of hazardous chemical waste generators in operation compared to nuclear waste generators, this implies that hazardous chemical waste management should be considerably more difficult than nuclear waste management.

III. Treatment and Waste Disposal

Hazardous Chemical Waste

Some of the main treatment processes that are currently in use for hazardous chemical waste are presented in Figure 2. They have been

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[16] DOE, *Spent Fuel Storage Requirements.*

[17] S. W. Plehn, *Final Environmental Impact.*

[18] DOE, *Management Summary.*

FIGURE 1

ANNUAL VOLUME COMPARISON: HAZARDOUS CHEMICAL VS. NUCLEAR WASTE

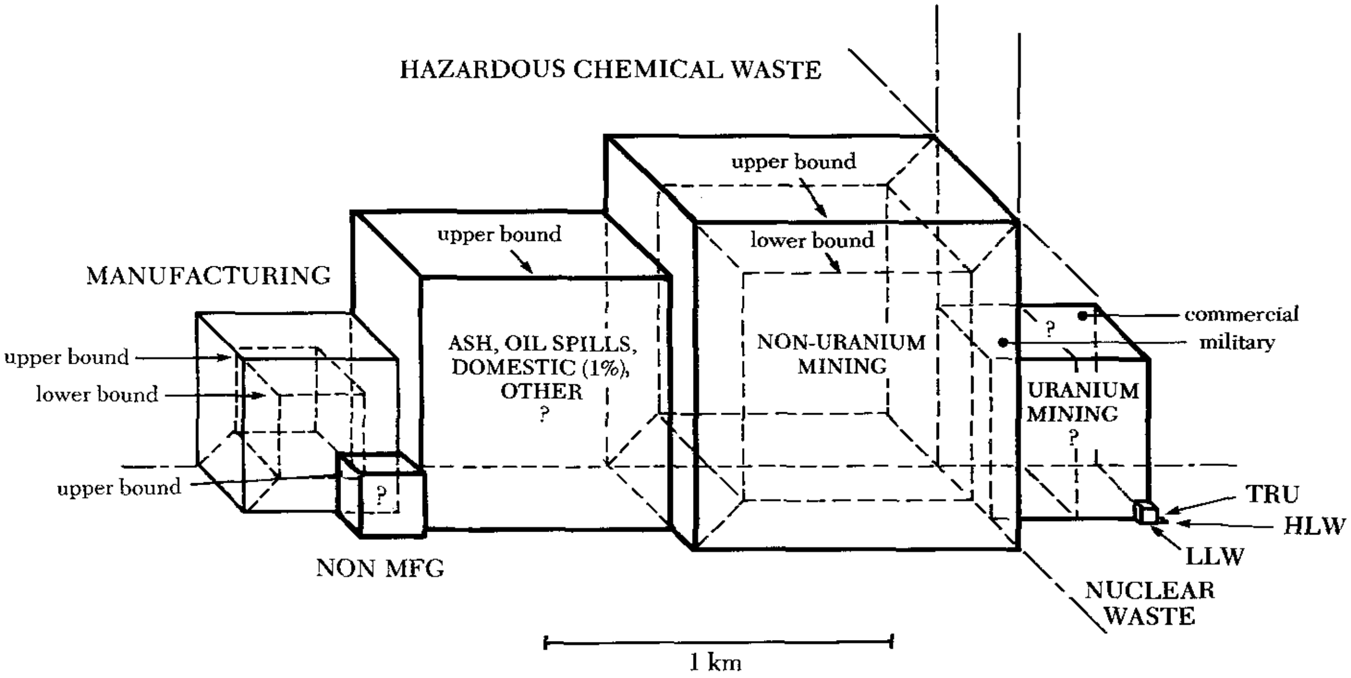
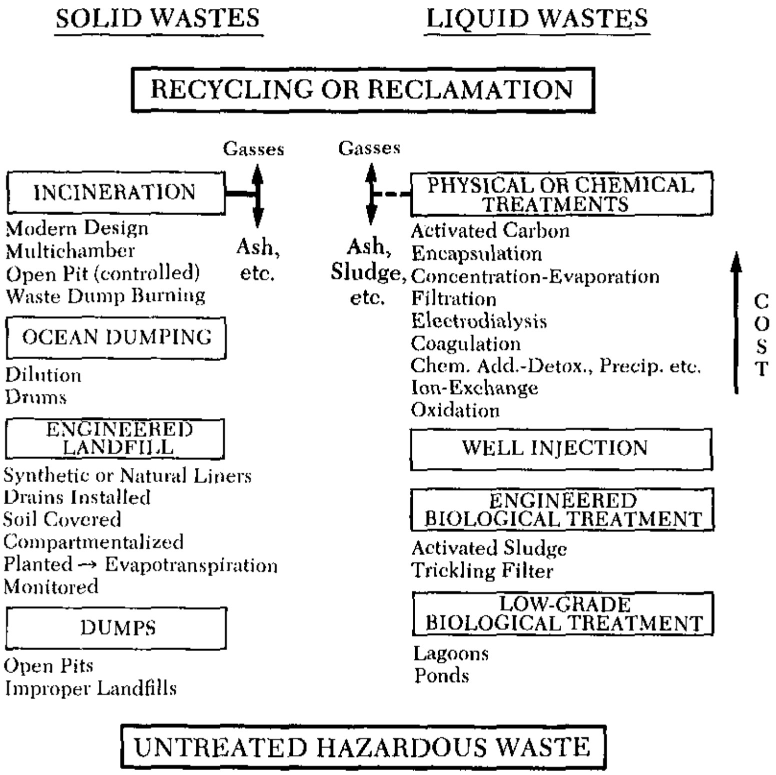


FIGURE 2
PRINCIPAL PROCESSES AVAILABLE FOR HAZARDOUS CHEMICAL WASTE TREATMENT



arranged from the bottom to the top of the page to correspond generally with trends of increasing cost. In terms of the estimated "volumes" of hazardous wastes treated or disposed of by commercial off-site facilities alone, Booz-Allen et al. estimate that: 36 percent are treated by "secure landfill"; 30 percent by "chemical, biological and physical treatment"; 11 percent by "deep well injection"; 8 percent by "land treatment/solar evaporation"; 6 percent by "incinerator"; 6 percent by "resource recovery"; and 3 percent by "secure landfill for chemical treatment wastes."[19] These percentages reflect only the amounts of waste treated by these commercial facilities, however, and do not accurately characterize the distribution of total amounts produced. A lot of hazardous materials are just abandoned at open dumps, scattered along the roadside, or released into open waterways. For many of the wastes, the highest-priced process is to convert them into usable products by recycling or reclamation. These processes could involve comminution, magnetic or density separations, and many other elaborate stages linked in various sequences. The least expensive waste process, but perhaps the most hazardous methodology, could be just to abandon it.

Many other processes have been designed, and their costs would undoubtedly fall between these two extremes.[20] An EPA list of "handling codes for treatment, storage and disposal methods" is presented in Table 1. Some of these intermediate processes can reduce concentrations of these toxic materials to fairly low levels, and others can stabilize/solidify acutely hazardous materials by using bentonite-cement mixtures or silicate matrices. Recently, a detoxification process using molten sodium metal reactions has been developed.

Some problems exist with some of the central methods used for hazardous waste, including incineration and landfill disposal. Incineration of different pollutants definitely reduces the volume of waste originally generated, but can also produce gas or liquid phase pollutants, ash and particulates, and quenched ash pile leachates. These could be quite toxic, but this would certainly depend on the type of

[19] Booz-Allen and Hamilton, Inc. and Putnam, Hayes and Bartlett, Inc., *Hazardous Waste Generation and Commercial Hazardous Waste Management Capacity – An Assessment,* SW-894, prepared for EPA Office of Water and Waste Management, December 1980.

[20] For a discussion of these processes, see 45 Fed. Reg. 98, p. 33063; N. P. Cheremisinoff, P. N. Cheremisinoff, F. Ellerbusch, and A. J. Perna, *Industrial and Hazardous Waste Impoundment* (Ann Arbor, Mich.: Ann Arbor Science Pub., 1979); D. Shultz, "Disposal of Hazardous Waste," Proceedings 6th Ann. Res. Symp., EPA 600/9-80-010, 1980; and R. B. Pojasek, *Toxic and Hazardous Waste Disposal, Processes for Stabilization/Solidification,* vol. 1 (Ann Arbor, Mich.: Ann Arbor Science Pub., 1979).

TABLE 1

EPA HANDLING CODES FOR TREATMENT, STORAGE AND DISPOSAL METHODS

1.	Storage
S01	Container (barrel, drum, etc.)
S02	Tank
S03	Waste pile
S04	Surface impoundment
S05	Other (specify)
2.	Treatment
(a)	Thermal Treatment
T06	Liquid injection incinerator
T07	Rotary kiln incinerator
T08	Fluidized bed incinerator
T09	Multiple hearth incinerator
T10	Infrared furnace incinerator
T11	Molten salt destructor
T12	Pyrolysis
T13	Wet Air oxidation
T14	Calcination
T15	Microwave discharge
T16	Cement kiln
T17	Lime kiln
T18	Other (specify)
(b)	Chemical Treatment
T19	Absorption mound
T20	Absorption field
T21	Chemical fixation
T22	Chemical oxidation
T23	Chemical precipitation
T24	Chemical reduction
T25	Chlorination
T26	Chlorinolysis
T27	Cyanide destruction
T28	Degradation
T29	Detoxification
T30	Ion exchange
T31	Neutralization
T32	Ozonation
T33	Photolysis
T34	Other (specify)
(c)	Physical Treatment
	(1) Separation of Components
T35	Centrifugation
T36	Clarification
T37	Coagulation
T38	Decanting
T39	Encapsulation
T40	Filtration
T41	Flocculation
T42	Flotation
T43	Foaming
T44	Sedimentation
T45	Thickening
T46	Ultrafiltration
T47	Other (specify)
	(2) Removal of Specific Components
T48	Absorption-molecular sieve
T49	Activated carbon
T50	Blending
T51	Catalysis
T52	Crystallization
T53	Dialysis
T54	Distillation
T55	Electrodialysis
T56	Electrolysis
T57	Evaporation
T58	High gradient magnetic separation
T59	Leaching
T60	Liquid ion exchange
T61	Liquid-liquid extraction
T62	Reverse osmosis
T63	Solvent recovery
T64	Stripping
T65	Sand filter

TABLE 1 (cont.)

EPA HANDLING CODES FOR TREATMENT, STORAGE AND DISPOSAL METHODS

T66	Other (specify)
(d)	Biological Treatment
T67	Activated sludge
T68	Aerobic lagoon
T69	Aerobic tank
T70	Anaerobic lagoon
T71	Composting
T72	Septic tank
T73	Spray irrigation
T74	Thickening filter
T75	Tricking filter
T76	Waste stabilization pond
T77	Other (specify)
T78 –79	[Reserved]
3.	Disposal
D80	Underground injection
D81	Landfill
D82	Land treatment
D83	Ocean disposal
D84	Surface impoundment (to be closed as a landfill)
D85	Other (specify)

waste burned and the process by which it was incinerated. For example, consider the case of polychlorinated biphenyls. Thermal decomposition at normal incineration temperatures (650°C to 850°C) produces tetra-, penta- and hexachlorobenzenes,[21] which are all definitely toxic substances.[22] Hexachlorobenzene was found to be carcinogenic in Syrian Golden hamsters.[23] In addition, TCDD, which is known to be highly toxic and also carcinogenic, is produced in some types of incinerators as well.

Toxic metals can be released by incineration as well. For example, in an experiment where domestic sewage sludge was pyrolyzed at 450°C and then incinerated, 20 percent of the cadmium and 25 percent of the lead originally present was lost to the "gas" phase of both stages.[24] At 800°C pyrolysis, 80 percent of the cadmium and 50 percent of the lead were released. In addition, about 1.4 liters of nitrogen oxides were produced per kilogram of dry sludge. Several industries

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[21] Cf. S. Budiansky and J. Josephson, "Waste Disposal Chemistry," *Environmental Science Technology* 14, no. 5 (1980):508.

[22] H. E. Christensen, et al., *Registry of Toxic Effects of Chemical Substances*, HEW, June 1976.

[23] Safe Drinking Water Committee, *Drinking Water and Health*, vol. 3 (Washington, D.C.: National Academy of Sciences Press, 1980).

[24] N. Takeda and H. Masakatusu, "Combined Process of Pyrolysis and Combustion for Sludge Disposal," *Environmental Science and Technology* 10, no. 12, (1976):1147.

have claimed that they have new methods of incineration that will meet the EPA's incinerator performance standards of greater than or equal to 99.99 percent destruction and removal of hazardous substances.[25] We hope they can.

The highest percentage of hazardous wastes generated and treated now are disposed of in landfills. It has been estimated that in 1980 75,700 industrial landfills were currently in operation. In addition, 50,644 active or inactive sites are estimated to possibly contain "potentially dangerous amounts of hazardous wastes."[26] Another study indicates 35 percent of 8,163 investigated landfill sites contain hazardous materials, 70 percent have "no lining," and 95 percent "have no groundwater monitoring system to detect toxic contamination." An additional study of 50 industrial landfills in 1977 indicated that about 80 percent of the landfills carrying specific types of hazardous chemicals were releasing a small fraction of these materials into the ground. A 1978 EPA study of municipal landfills identified 14,000 active sites, but only 35 percent were "in compliance with state regulations."[27]

Amounts of landfill leachates generated depend mostly on what types of wastes are buried, the weather conditions, and landfill designs. Areas that have high precipitation and low amounts of evapotranspiration favor landfills to produce relatively large quantities of leachate.

The vulnerability of current landfills to rainfall has recently become quite apparent, and this can be enhanced by construction failures. Landfills appear to be subject to decomposition-oriented differential pressure development and improper slope gradients constructed at the side of a landfill. This leads to the formation of cracks at the surface up to 0.5m wide, a very ready uptake of precipitation, followed by large-scale production of landfill leachates.[28]

At least some degree of care should be taken with the construction of hazardous waste landfills, which are increasing in number rapidly. If at all possible, geologic formations such as limestone terrain should be avoided because fractured rock and karst flow systems are so easy to pollute. Thick shales or clay mineral deposits should be highly favored because of very low groundwater permeabilities and high

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[25] 46 Fed. Reg. 15, January 23, 1981, p. 7666.

[26] Council on Environmental Quality, *Eleventh Annual Report.*

[27] Ibid.

[28] Cf. J. P. Murray, et al., "Groundwater Contamination by Sanitary Landfill Leachate and Domestic Wastewater in Carbonate Terrain: Principal Source Diagnosis, Chemical Transport Characteristics and Design Implications," *Water Resources* 15 (1981):745.

adsorptive capacities. Landfill sites should be excavated in such a way that their containment space does not intercept saturated groundwater flow systems.

Many supposedly better landfills are currently advertised by various manufacturing industries. A pipe system to collect spill installed below the landfill might help, but can hardly be expected to collect all the fluid from leaks in a geometrically complex garbage dump. Monitoring and filling surface cracks as well as coverage under the top of the landfill with plastic liners and gas-release systems markedly reduce the amounts of leachate produced. Gas-release systems might be used for methane recovery and use. Coverage of the "bottom" would not do much. Precipitation could continuously collect in the lined landfill until it would resemble a bathtub, and leachate would begin to pour out of the lowest "leaks" in the liner.[29]

A dilemma is bound to arise, even if the "best" landfill procedures begin to be installed. How much land and how much of the eventually usable fraction of the solid waste that we are burying should we be willing to discard? All the resources ending up in landfills would be exceptionally difficult to recover, as natural sources of these various materials become increasingly scarce. At this stage, only two percent of hazardous wastes are being recycled.[30] In addition, even if a landfill passes the current EPA 30-year post-closure requirement, hazardous components such as toxic metals and many chlorinated organics would still be preserved for future release.

Some of the toxic components leaking out of landfills or "unlined" lagoons are beginning to contaminate water supplies. To some extent, therefore, they can affect the food chain of man via bioaccumulation and progressive ecosystem food-chain concentration. There could even be direct contact with released hazardous materials, which could lead to increased exposure and risk. EPA is becoming increasingly aware of this problem and has come out with a new list of hazardous landfill substances and a set of landfill owner regulations.[31] It has also come up with a new financial method for cleaning up severe hazardous waste disposal sites—Superfund—and lists of methods of how it could be used.[32] These chemicals exhibit some probability of increasing the risk of adverse, human-health effects such as cancer. It would depend on what chemicals were released

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[29] 47 Fed. Reg. 49, March 12, 1982, p. 10972.

[30] Council on Environmental Quality, *Eleventh Annual Report.*

[31] 46 Fed. Reg. 24, February 5, 1981, p. 11126.

[32] 47 Fed. Reg. 49, March 12, 1982, p. 10972.

and how much a community might receive, however, before we could say anything about the magnitude of imposed risk.

Nuclear Waste

High-level wastes, mentioned before, principally consist of uranium oxide fuel pellets packed within zircalloy stainless steel tubes. These tubes are removed from reactor cores after burnout and placed in pools adjacent to reactor facilities. The pools are to keep fuel rods cool by self-generated thermal pumping and thermal conduction. Several different methods for final disposal of nuclear waste have been suggested. These include mined geologic disposal, subseabed disposal, very deep hole disposal, rock-melting disposal, island disposal, ice sheet disposal, deep well injection disposal, space disposal, waste partioning and transmutation, and chemical resynthesis.[33]

Mined geologic disposal is considered to be the most appropriate at this time. The generated waste can be reprocessed or buried *in toto*. If the reprocessing design for disposal of HLW becomes politically acceptable and is done, the waste can be processed with acid-base and other treatments to remove the uranium and plutonium for recycling. The residual collection of fission products and actinides can then be incorporated into glass or crystalline matrices and inserted into stainless steel or copper waste canisters. If not, fuel rods can be assembled into waste canisters with stabilizer material to effectively separate them and block neutron flux. The Swedes have considered lead as the optimum stabilizer for this case.[34] Canisters could be sequentially packed into several different containers at the same time to be protected against possible geochemical alterations leading to canister corrosion.

In deep-mined geologic sites, 500–1,000 meters below the surface, either type of canister would be packed in arrays, which would keep generated thermal profiles of the system within acceptable levels. The Swedes planned burial for 30-year-old (in storage) spent fuel rod canisters in rows 25 meters apart, with canisters placed at every 6 meters along the rows. This method of packaging has been calculated to generate thermal gradients leading to a maximum rock temperature of 60°C.[35] These zones would be picked based on tectonic stability, low groundwater permeability and political availability.

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[33] DOE-NRC, *Storage and Disposal*.

[34] KBS, *Handling and Final Storage of Unreprocessed Spent Nuclear Fuel*, vol. 2 *Technical* (Stockholm: Karnbranslesakerhet, 1978).

[35] Ibid.

Geologic environments such as tectonically stable salt domes, salt beds, granites, basalts, and tuffs have already been tentatively selected for burial, to start about the year 2000.[36] Immediately after replacement, they would be surrounded by adsorbent backfill packaging with such material as bentonite, zeolites, other clay minerals, etc., or various mixtures. Elaborate geochemical studies of how the backfill mixtures would respond to the low-grade thermal pulse after nuclear waste burial are currently being done at Sandia.[37]

After construction of the repository and disposal of the waste, shafts would be filled with materials such as bentonite-sand mixtures to allow for recovery, if required. HLW generated by nuclear fuel services would be vitrified, incorporated into canisters, and buried in a similar fashion.

Subseabed disposal of high-level wastes has also been considered.[38] This is due to the possibility that no state government may eventually accept repository construction for political reasons. On the other hand, international agreements might very well prevent subseabed disposal in the future. In either case, however, it could be useful to know whether or not other options are available. This would involve packaging the waste into chemically stable canisters and dropping them or inserting them in a random or planned array ~30m into bottom sediments on tectonically stable floors of the deep ocean.

Cohen has suggested that if we consider disposing of nuclear wastes in the deep oceans, the cancer risk is possibly greater than for disposal on land but it can be calculated with greater certainty, and the chance of catastrophe is negligible.[39] Following this thinking, we suggest a rule:

> If the expected lifetime of the waste exceeds the expected secure lifetime of the repository, it could be environmentally superior, and superior for public health, to dispose of the waste in the deep oceans rather than on land.

In the past, TRU—mostly contaminated laboratory or processing equipment—has been disposed of in landfills, usually at military sites along with LLW. In 1962, and shortly thereafter, six commercial burial sites were developed.[40] These sites are located at Barnwell,

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[36] DOE-NRC, *Storage and Disposal.*

[37] Personal communication, J. L. Krumhansel, 1981.

[38] DOE-NRC, *Storage and Disposal.*

[39] Cf. B. L. Cohen, "Ocean Dumping of High Level Waste – An Acceptable Solution We Can Guarantee," *Nuclear Technology* 47 (1980):163.

[40] DOE, *Spent Fuel and Waste Inventories.*

South Carolina; Beatty, Nevada; Hanford, Washington; Maxey Flats, Kentucky; Sheffield, Illinois; and West Valley, New York. Only the sites at Barnwell, Beatty, and Hanford (or Richland) remain open. The Barnwell site has never accepted TRU waste, only LLW. In the TRU waste buried at these sites, only 123.4 kg of transuranic elements have been included. After issuance of the AEC directive in 1970, TRU wastes have been placed in retrievable storage.[41] Current DOE plans involve their careful, deep geologic burial once a repository has been built. Technology such as incineration and electrodialysis is currently under consideration for preliminary volume reduction.

Low-level wastes are now disposed of in the three landfills mentioned above. These landfills are generally constructed by digging deep trenches and filling them with packaged LLW. Once filled, the trenches are covered with all the soil and geologic materials taken out.[42] These landfills are covered with a thicker layer than most hazardous chemical waste dumps, and their LLW volumes are much less degradable than domestic waste. In addition, these sites are continuously monitored. For these reasons, the landfills may very well generate less contaminated leachate than conventional hazardous chemical waste operations. This would be particularly valid in the case of the Beatty, Nevada, and Hanford, Washington, sites; two of the three are currently operating because of the relatively low rainfall and relatively high evaporation rates at their locations. Small quantities of the isotopes included in the waste may nonetheless be leached out, but hopefully not before most of them have undergone radioactive decay. Questions do remain, however, concerning how much will be released and where it will go. At least we know that leakage at Beatty will be confined by geologically isolated basins, and leakage at Hanford will be diluted by enormous volumes of the Columbia River and the Pacific Ocean after very slow migration through highly adsorbent tuff.

Uranium mining wastes are also a result of nuclear industry operations. The hazard associated with this type of waste is emission of the decay products radon-222 and thorium-230. Since radon-222 has a half-life of 3.823 days, only a thin covering of soil, perhaps only two feet thick, can effectively block release. These waste piles also need stabilization against wash-out erosion and probably long-term surveillance and maintenance. DOE has developed a remedial action

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[41] Ibid., and DOE, *Program Summary Document.*

[42] DOE, *Program Summary Document.*

program for uranium mining wastes and is interfacing with state agencies and NRC in this regard. It plans to complete this project by fiscal year 1985.[43]

IV. Fate and Persistence

One of the central issues in determining how much risk hazardous chemical and nuclear wastes might develop is the fate and persistence of their hazardous components after disposal. In other words, where do they go and how long do they stay? If we are trying to estimate the potential health effects imposed by a waste disposal facility, we must at least have a good estimate of the amount of chemicals or radionuclides that would eventually be available for exposure.

Predicting these amounts will require determination of the stability of each given substance involved and the tremendous assortment of physical mechanisms and chemical reactions involved, as well as how fast these processes operate. A list including a few of these processes important for hazardous wastes is presented in Table 2. Determination of these parameters for one compound under very simple reaction conditions would take a large amount of effort. In addition to these parameters, many other important biological processes are involved, such as metabolism, bioaccumulation, biodegradation, sulfate reduction, and photosynthetic sulfide oxidation.

A small amount of hazardous products or wastes are spilled in transportation accidents. This fits into the category of fate. In fiscal year 1979, 1,766 hazardous material incidents were reported to EPA regional offices. Between 38 percent and 55 percent of these were transportation accidents involving rail, truck, ship-barge, and aircraft industries.[44]

A number of mathematical models have been built, characterizing highly limited systems. These refer particularly to nuclear waste disposal and chemical transport considerations related to agricultural problems. Many of these have been presented in the soil science literature. Most of these models are based principally on numerical analysis of convective-dispersion equations with various chemical or biological reactions included as well as pedologic media adsorption characteristics. EPA has developed a microcosm-oriented model (EXAMS) that approaches some toxic waste questions with compart-

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[43] Ibid.

[44] EPA, *Hazardous Materials Incidents Reported to U.S. EPA Regional Offices from October 1977 through September 1979*, January 1980.

TABLE 2

A FEW OF THE BASIC PHYSICAL OR CHEMICAL PROCESSES IMPORTANT FOR THE FATE AND PERSISTENCE OF HAZARDOUS AND NUCLEAR WASTES

Physical Processes	Chemical Processes
Gravity	Reactions
Pressure	Phase transformations
Temperature	gas, liquid, solid
Atmospheric circulation	Temperature dependence
Streamflow	Reversible reactions
Groundwater flow	Irreversible reactions
unsaturated media	Inorganic reactions
saturated media	Organic reactions
porous media	Complex formation
fractured media	Oxidation, Reduction
Particle entrapment in flowing systems	Adsorption
	adsorption isotherms
Colloid stability	hydrophobic processes
double-layer interaction	hydrophyllic processes
Lifshitz-Van der Waals potentials	retardation factors
Dispersion	Thermodynamics of reactions
Diffusion	ΔG°, ΔH°, S°, C_p, etc.
Geophysical processes—Tectonic	K, ΔG_{rxn}, μ_i, γ_i, $[x_i]$, a_i, etc.
earthquakes	ΔG_{ads}, θ, etc.
faults	Aqueous condition measurements
volcanic activity	pH, Eh, pe
intrusive activity	Photoreactivity
Erosion	e.g., photooxidation
Solar light flux	Chemical kinetics
Radioactive decay	1st, 2nd, etc. order
	catalysis

mental analysis.[45] KBS has assembled three models sequentially—ORIGEN, GETOUT, and BIOPATH, which look at suspected health and ecosystem effects potentially resulting from their planned HLW disposal sites.[46] A different mathematical approach is used for each stage. Many possibly important types of chemical reactions such as irreversible adsorption components, new-phase precipitation, or recrystallization with phase inclusion of various hazardous compo-

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[45] D. M. Cline, "EXAMS: an Exposure Analysis Modeling System," preliminary draft, EPA Environmental Research Laboratory, Athens, Ga., 1979.

[46] KBS, *Handling and Final Storage.*

nents are hardly incorporated into these models. This leads to uncertainty. Substantially expanding and combining these types of models to include complex chemical reactions and statistical uncertainty—not just highly simplistic terms such as retardation factors—would be very helpful in assessing potential risks due to different methods and types of disposal. Although a careful study and complex mathematical description of all the possible important controlling chemical reactions with the earth have yet to be done, especially with hazardous wastes, we can begin to make preliminary assessments about the hazards of chemical and nuclear wastes by beginning to develop and expand computer predictions about expected risks for hazardous wastes.

One key issue between hazardous chemical waste and nuclear waste has to do with degradability and radioactive decay. *Metals such as arsenic, which are not radioactive, are essentially stable for the lifetime of this planet.* Some organics can be oxidized quite readily, especially when exposed to solar-light flux in the atmosphere. Others, such as chlorinated or hydrogenated aliphatic compounds and many polycyclic aromatic compounds, appear quite stable within buried, reducing environments. An excellent review is presented by M.A. Callahan, et al. concerning known fate and persistence of the 129 EPA Clean Water Act priority pollutants.[47]

Radionuclides, however, definitely decay. Some of them have short half-lives. In Figure 3 the total number of calculated cancer doses representative of one TMT (initial) of fuel rods is plotted against the years after removal from a reactor. The number of doses present within the uranium ore required to generate this much fuel is included as well. With unreprocessed spent fuel, we intersect the same number of doses estimated for the original uranium ore, about 1,000 years after spent fuel removal from the reactor. It progresses to about a factor of five fewer doses after that. The only increase in the hazard potential of spent fuel after 1,000 years might be due to radionuclide chemistry changes with respect to geologic media transport. This will be summarized briefly in relation to Oklo. It would be much more difficult to sum the potential hazardous organic chemical toxicities over time.

Rather than discuss the detailed environmental chemistry of all these toxic substances at this stage, in comparing hazardous chemical wastes with nuclear wastes we shall discuss two important events for which some measure of knowledge is available. The first is Love

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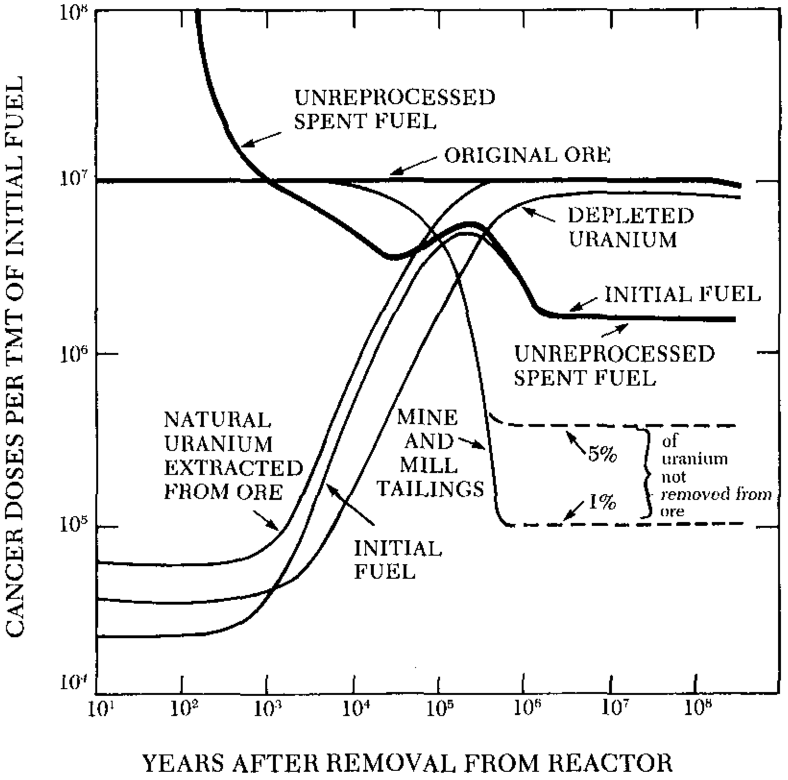
[47] M. A. Callahan, et al., *Water Related Fate of 129 Priority Pollutants*, vol. 1, EPA-440/4-79-029a, 2, EPA-440/4-79-029b, December 1979.

FIGURE 3
COMPARISON OF RADIOACTIVE HAZARD DECAY PROFILES OF URANIUM ORE AND PRODUCTS OF VARIOUS METHODS OF USAGE, INCLUDING SPENT REACTOR FUELS[48]



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[48] This figure was originally drawn by E. A. Crouch, personal communication.

Canal, Niagara Falls, New York and the second is the natural reactor at Oklo, Gabon, Africa.

Love Canal

Love Canal was originally built by William T. Love in the 1890s to feed a hydroelectric power-generating station, but digging was terminated shortly after construction began. A map is presented in Figure 4. Between 1942 and 1953, Hooker Electrochemical Company disposed of 21,800 tons of hazardous chemical wastes in this location.[49] A list of these has been put out by Hooker Chemical Company.

An elementary school, 99th Street School, was built on top of the landfill in 1954 and throughout the fifties and sixties, housing was developed around the site. Removal of a good portion of the landfill coverage could well have increased development of leachate and migration to buried stream beds in the area. By the mid-1960s this led to odors and visible pollution problems in the surrounding neighborhood. A list of the level of hazardous contaminants in the atmosphere, the groundwater, and the soil is presented in Table 3.[50] Most of these chemicals are known animal carcinogens. The carcinogenic potency for humans can be estimated by analogy,[51] but this has yet to be done with all of the data from Love Canal.

The population living in the region surrounding the canal at 97th and 99th Street that contains 99 houses (section I on map) was relocated between August 1978 to January 1979 by the New York State government, and the 99th Street School was closed. In February 1979 all the pregnant women and two-year-old children who lived in the region between 97th and 103rd Street, were asked to relocate. The evacuation section has been expanded to the area shown in section II down to Frontier Avenue. Significant numbers of houses in this area were still being purchased in 1981 and paid for by the federal government.

Careful epidemiologic investigations of possible health effects have been carried out by the New York State Department of Health and

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[49] New York State Department of Health, *Love Canal, A Special Report to the Governor and Legislature*, April 1981; B. Paigen, "Love Canal – Lessons for Society," presentation to Banbury Conference, June 8–10, 1979; Interagency Task Force on Hazardous Waste, "Draft Report on Hazardous Waste Disposal in Erie and Niagara Counties," New York, March 1979; and personal communication, T. Gilles, Office of New York Attorney General Robert Abrams, 1982.

[50] New York State Department of Health, *Love Canal*.

[51] Cf. E. A. Crouch and R. Wilson, "Interspecies Comparison of Carcinogenic Potency," *Journal of Toxicology and Environmental Health* 5 (1979); also personal communication, 1981.

FIGURE 4
LOVE CANAL

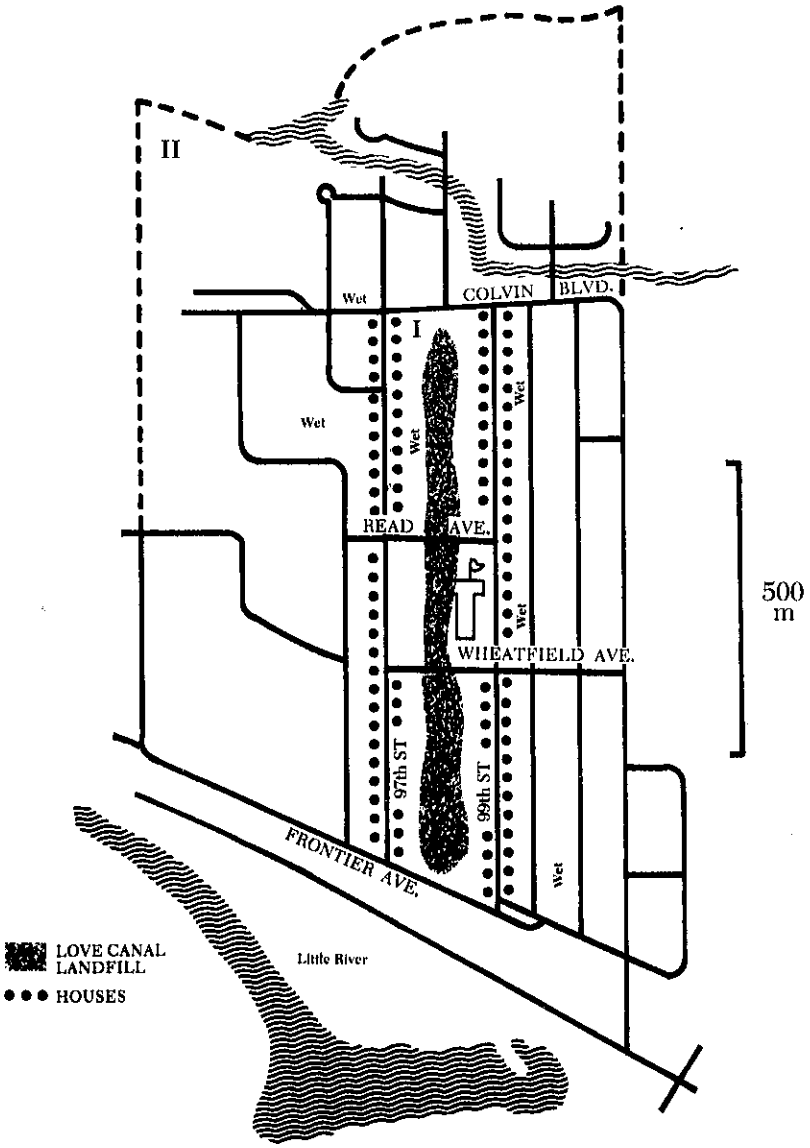

TABLE 3

CHEMICALS FOUND AT LOVE CANAL

Chemical	Water and Leachate	Air	Soil and Sediment
Benzene	ID[a]	522.7 μg m^{-3}	< 0.1–0.8 μg kg^{-1}
α-Benzene hexachloride	3.2 μg l^{-1}	0.002–0.1 μg m^{-3}	ID
β-Benzene hexachloride	38 μg l^{-1}	3 μg m^{-3}	ID
δ-Benzene hexachloride	6.9 μg l^{-1}	0.4 μg m^{-3}	ID
γ-Benzene hexachloride (Lindane)	50 μg l^{-1}	ID	20 mg gm^{-1}
Carbon tetrachloride	ID	5.0 μg m^{-3}	
Chlorobenzene	10 mg l^{-1}	0.1–172 μg m^{-3}	0.4–2.9 μg kg^{-1}
Chloroform	0.2–3.9 μg l^{-1}	0.5–24.0 μg m^{-3}	0.2–2.3 μg kg^{-1}
Chlorotoluene	75 mg l^{-1}	0.008–7650 μg m^{-3}	ID
Dichlorobenzene	3 mg l^{-1}	< 0.3–100.5 μg m^{-3}	240 μg kg^{-1}
Dichloroethane	0.2–4.8 μg l^{-1}		< 0.4–2 μg kg^{-1}
Dichlorotoluene	95 μg l^{-1}	< 18–74 μg m^{-3}	
1,3-Hexachlorobutadiene		22–114 μg m^{-3}	
Pentachlorobenzene	2.5 mg l^{-1}	0.5 mg m^{-3}	58 μg kg^{-1}
Tetrachlorobenzene	5 mg l^{-1}	0.01–74 μg m^{-3}	11–100 μg kg^{-1}
Tetrachloroethylene	< 0.3–0.8 μg l^{-1}	< 0.2–52 μg m^{-3}	< 0.3 μg kg^{-1}
Tetrachlorotoluene	1 mg l^{-1}	< 0.01–0.97 μg m^{-3}	ID
Trichlorobenzene	52 μg m^{-3}	0.03–84 μg m^{-3}	34–64 μg kg^{-1}
Trichloroethylene	52 mg l^{-3}	73 μg m^{-3}	ID
Trichlorophenol	0.1–11.3 μg l^{-1}	ID	0.5–90 μg kg^{-1}

TABLE 3 (cont.)

CHEMICALS FOUND AT LOVE CANAL

Chemical	Water and Leachate	Air	Soil and Sediment
Trichlorotoluene	34 mg l^{-1}	0.05–43.7 μg m^{-3}	ID
Toluene	250 mg l^{-1}	0.1–6.2 mg m^{-3}	< 0.1–104 μg kg^{-1}
Dioxin (TCDD)	1.4–5.1 ppt		< 2 ppt–312 ppt
1,2-Dichloroethylene	"0.1–0.1 μg l^{-1}"	334 μg m^{-3}	
PCB	0.64 mg l^{-1}		2–6 ppm
Methylene Chloride	< 0.3–0.3 μg l^{-1}	< 0.7–11.6 μg m^{-3}	
Bis (2-ethylhexyl) phthalate	8.1–24 μg l^{-1}		

SOURCE: These analyses are a summation of work carried out by the Toxicology Institute, Division of Laboratories and Research, New York State Department of Health and various laboratories of the U.S. Environmental Protection Agency and their subcontractors.

[a] ID—Identified but not quantitated.

NOTE:
μg = micrograms (10^{-6} grams),
mg = milligrams (10^{-3} grams),
l^{-1} = per liter,
ppt = parts per trillion, and
ppm = parts per million.

personnel from Roswell Park Memorial Institute.[52] The following medical problems have been studied:

MEDICAL EXAMINATION TESTS	RESULTS—LOVE CANAL
1. Liver function	97th–99th St., slight (−) effects. Relocation showed a return to normal for most cases.
2. Anemia	Within expected limits.
3. Chloracne	No documented evidence.
4. Asthmatic, respiratory condition	No excessive incidence.
5. Cancer	No apparent excess.
6. Convulsive disorders	No excessive incidence.
7. Congenital defects	No significant excess for total Love Canal population. Two control groups: one in Canada and the other just north of Love Canal across Colvin Blvd. Possibly some excess for people living in wet areas where buried streambeds (swales) are located.
8. Low birth weights infant ≤2500 grams	Slight increase in low birth weights recorded on 99th Street and on wet areas.
9. Spontaneous abortions	*Significant increase for those living on 99th Street and in wet areas.* This was between 1959 (just after home building) and the early '70s. Spontaneous abortion rates in these areas reached a peak about three times higher than those living in dry areas at Love Canal in the early '60s.

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[52] New York State Department of Health, *Love Canal.*

The chromosomes of 36 Love Canal residents were examined by Biogenics Corp., of Houston, Texas, and 11 were judged to be "somewhat abnormal." Controls have not been taken, however, so these effects have been considered controversial.[53]

It is expected that cancer induced by chemicals will not be observable until 20 years after the exposure. The relation between lung cancer incidence and cigarette sales indicates this delay.[54]

It is likely that the individuals who have been evacuated from Love Canal will be asked to participate in epidemiologic data collection for a long time in order to provide data regarding cancer incidence with some degree of known environmental exposure rates.

We have attempted to gain some perspective on the actual risk paid by using the concentrations of various chemicals presented in table 3. To calculate the lifetime dose(d), we anticipate that no more than one percent of the water and leachate will have entered a drinking water supply or distribution system. Since man drinks about 2 liters per day, we assume that the maximum consumption is 0.02 liters of leachate per day. We also assume that the exposed population breathes this air all the time, i.e., 22 cubic meters per day per person. We therefore calculate a daily intake (α) in milligrams and divide by the body weight (70 kilograms) of an exposed individual. We assume further that cancer incidence is proportional to intake with the constant of proportionality the same as that in rats and mice. This is expressed as daily intake as a fraction of body weight. The carcinogenic potency (β) is then taken from human and animal data.[55] The product $d\beta$, if less than 1, is the expected lifetime cancer incidence, or risk (R), from an individual's lifetime exposure. We show this in Table 4.

We also assume that at low doses, deaths from toxic effects are less than those from cancer (animal data suggest this) and therefore that this number is an estimate of the total death rate from this cause. We note that two of the chemicals give lifetime risks close to 10^{-3}, or average annual risks close to 10^{-5}. These are in the region where notice must be taken, especially since other chemical exposure exists here as well.

However, none are in the region of lifetime risk of 1/10 or more. In a small sample of people exposed (500 or less), the total risk

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[53] Ibid.

[54] Cf. J. Cairns, *Cancer: Science and Society* (San Francisco: W. H. Freeman and Co., 1978).

[55] E. A. Crouch and R. Wilson, "Interspecies Comparison."

TABLE 4

RISK ESTIMATES FOR SOME OF THE COMPOUNDS IN TABLE 3.

Chemical	Potency	Maximum[a] Lifetime Risk for Lifetime Exposure		
	β mg^{-1} kg day	^{R}air (22m^3 day^{-1})	^{R}water (0.02 ℓ day^{-1})	Total Risk from Data Avail.
Benzene[b,c]	1×10^{-3}	1.6×10^{-4}	—	1.6×10^{-4}
α-Benzene Hexachloride[d]	11.1	3.5×10^{-4}	1.0×10^{-5}	3.6×10^{-4}
β-Benzene Hexachloride[d]	1.84	1.7×10^{-3}	2.0×10^{-5}	1.7×10^{-3}
γ-Benzene Hexachloride–[Lindane][d]	1.33	—	1.9×10^{-5}	1.9×10^{-5}
Carbon Tetrachloride[b]	2.5×10^{-3}	3.9×10^{-6}	—	3.9×10^{-6}
Chloroform[b,c]	$<1 \times 10^{-3}$	$<7.5 \times 10^{-6}$	$<1.1 \times 10^{-9}$	$<7.5 \times 10^{-6}$
Dichloroethane[b]	3.3×10^{-3}	—	4.5×10^{-9}	4.5×10^{-9}
PCB[d]	4.34	—	7.9×10^{-4}	7.9×10^{-4}
Tetrachloroethylene[b]	1×10^{-3}	1.6×10^{-5}	2.3×10^{-10}	1.6×10^{-5}
Trichloroethylene[b]	4.5×10^{-3}	1.0×10^{-4}	6.7×10^{-5}	1.7×10^{-4}
TCDD	$\sim 10^4$	—	1.5×10^{-5}	1.5×10^{-5}
TOTAL		2.3×10^{-3}	9.2×10^{-4}	3.2×10^{-3}

[a] Maximum values of chemicals found were used. [b] Potency taken from Crouch and Wilson.[56]
[c] Data from human exposure, the other potency data taken from animals—average of data compiled
[d] Potency taken from Voytek.[57]

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[56] Ibid.

[57] P. E. Voytek, "Aspects of Risk Assessment Strategy," in *Assessment of Health Effects at Chemical Disposal Sites, Proceedings of Rockefeller University, N.Y. Symposium,* June 1–2, 1981, p. 155.

computed may imply induction of about one case of cancer. With this data it is unlikely that significant increased cancer incidence will be found. Just recently, much higher levels of dioxin have been found at Love Canal. These are up to 17.2 ppm in basement sumps, 0.3 ppm in a creek bed or storm sewer, and about 0.03 ppm in soil (see T. Gilles, n.49). This indicates that the New York State Health Department's previous data, examined above, may have been far too low, and a significant increase in cancer rates may develop in the exposed population. In addition, exposure to several cancer-causing agents acting together may be worse than the effect of the sum of each separately—known as synergism.

A remedial construction plan was started in 1979 for collection and treatment of the landfill leachate as well as to try to block further leachate generation and contamination of the surrounding area. The federal government had spent over $21 million by the end of 1980. Suits against Hooker Chemical Company currently total somewhere between $12 *billion* and $14 *billion*.

The Oklo Natural Reactor and Implications Concerning Nuclear Waste Disposal

About 2.05 ± 0.03 billion years ago several zones which now exist in a French uranium mine at Oklo, Gabon in central west Africa went critical with respect to nuclear fission.[58] This involved water-moderated neutron flux in concentrated uraninite-pitchblend deposits, up to 70 percent uraninite, in zones which measured about 20 meters in diameter and 0.5 to 1.5 meters thick.[59] At this time these deposits had a natural uranium-235/uranium-238 ratio of 3.85 percent, since uranium-235 decays a little faster than uranium-238. This ratio is quite comparable to that used in current LWR reactor facilities.

Oklo is the only clearly demonstrated reactor known to have existed. It provides considerable information as to what we can expect with aged nuclear waste. Many of the site conditions favored leakage but very little of the hazardous radioactive nuclides appear to have leaked very far.

A geologic map and cross section are presented in Figure 5.[60] Extended discussions of the geologic environment surrounding Oklo

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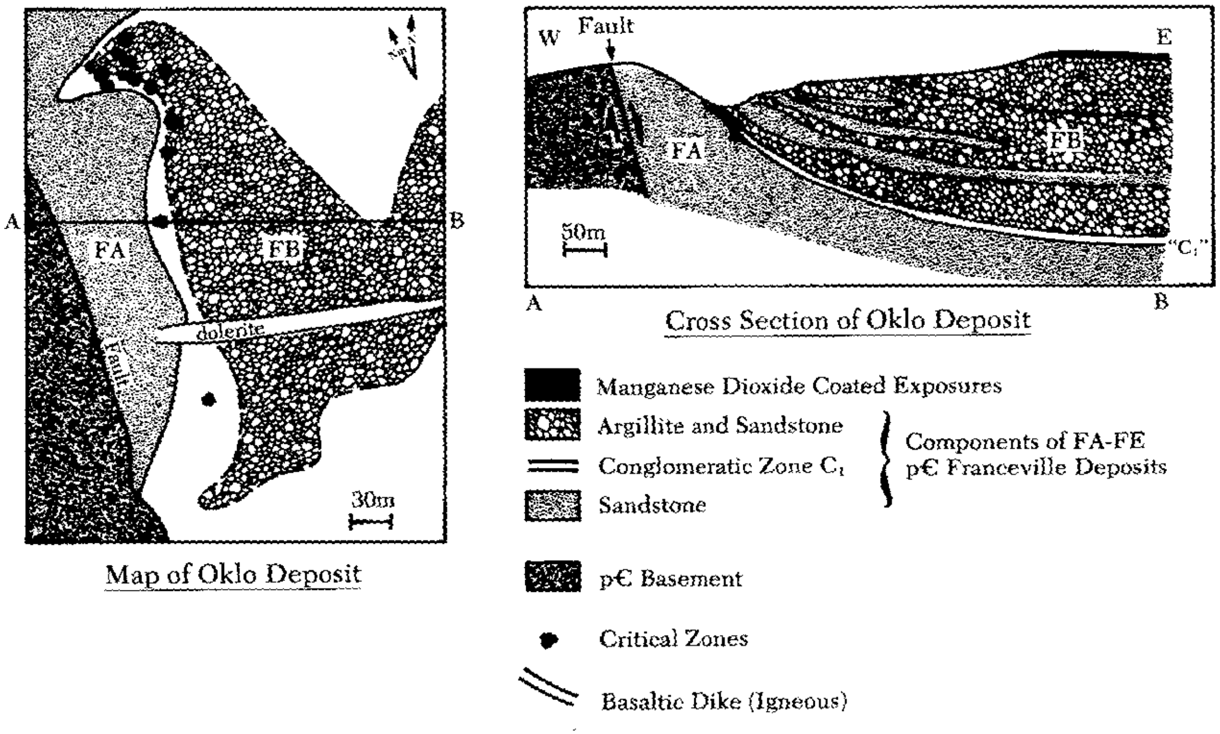
[58] A. Gankarz, "U-Pb Age (2.05 × 10^9 Years) of the Oklo Uranium Deposit," *IAEA Symposium Proceedings*, IAEA-TC-119/40, Vienna 1978.

[59] G. Branche, et al., "Données Chimiques et Mineralogiques sur les Gisements D'Oklo," *IAEA Symposium Proceedings*, IAEA-SM-204/17, Libreville, Gabon, 1975, p. 119.

[60] Gauthier-Lafaye, et al., "Données Nouvelles sur l'Environment Geologique des Reacteurs Naturels," *IAEA Symposium Proceedings*, IAEA-TC-119/2, Vienna, 1978, p. 35.

FIGURE 5

GEOLOGIC MAP AND CROSS SECTION OF OKLO NATURAL REACTOR
(ADAPTED FROM GAUTHIER-LAFAYE ET AL.)



Map of Oklo Deposit

Cross Section of Oklo Deposit

can be found in the proceedings of two symposia held by the International Atomic Energy Agency (IAEA) in 1975 and 1977.

There have been many investigations to discover whether or not fission products or actinides generated in the Oklo critical zones have ever leaked out during their approximately 600,000 year time period of fission.[61] An excellent paper compiling the work in this area was written by E. A. Bryant et al.,[62] which we summarize in Table 5.[63-65] We have also included other important phenomena.

Oklo demonstrates that wastes can be buried for exceptionally long periods of time with very little release of the highly toxic radionuclides. Even in the apparently highly permeable geologic formations in which it was originally found and perhaps deposited (conglomerates) that have been hit by faults and magmatic intrusions, the exceptionally hazardous materials (e.g., plutonium) appear to be effectively retained. They remained in the critical zones until completely decayed.

The conditions of Oklo appear to include tectonic stability and some degree of adsorbent material (clay) enclosure. We should certainly be able to improve on the Oklo geologic site by providing: deep burial in "protective" geologic formations, e.g., thick shales, which are very well redox buffered at low potentials; attention to thermal generation to reduce the possibility of fracturing and "hot spring" formation; chemically and perhaps mechanically optimized canister surrounding adsorbent packaging; ^{129}I separation and special waste treatment for long-lived containment (if waste reprocessing is allowable); waste enclosure in glass or Synrock; and canister coverage by stainless steel or copper. It is quite clear that current technology has most of these objectives already in mind.[66] Unfortunately, we cannot yet be as positive about long-term disposal of a large number of different, high-volume hazardous chemical wastes.

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[61] R. Hageman, et al., "Estimation de la Durée de la Reaction, Limitations Imposées par les Données Neutroniques," *IAEA Symposium Proceedings*, IAEA-SM-204/28, Libreville, Gabon, 1975, p. 415.

[62] E. Bryant, et al., "Oklo, an Experiment in Long Term Geologic Storage, Actinides in the Environment," A. Friedman, ed., in *ACS Symposium*, Series 35 (Washington, D.C.: American Cancer Society, 1976), p. 89.

[63] Ibid.

[64] ORNL, *ORIGEN Isotope Generation and Depletion Code-Matrix Exponential Method*, CCC-217, May 3, 1976. Run courtesy of Steven G. Oston, TASC, Reading, Mass.

[65] D. Rai and R. J. Serne, *Solid Phases and Solution Species of Different Elements in Geologic Environments*, PNL-2651, March 1978; and B. Allard, H. Kipatsi, B. Torstenfelt, *Sorption av langlivade radionukider i lera ock berg Del 2, KBS Teknisk Rapport 98*, Stockholm, Sweden, 1978.

[66] DOE-NRC, *Storage and Disposal.*

TABLE 5

MIGRATION OF FISSION PRODUCTS AND ACTINIDES IN THE "ZONE 2" REACTOR AT THE OKLO MINE, ELEMENT AND MIGRATION BEHAVIOR COMPILED BY E.A. BRYANT ET AL.[63]

Element	Migration Behavior	Percent Left After [10 years][a]	Other Important Characteristics[b]
Kr	Measurable traces, 0.01 to 1% remaining	1.53%	^{85}Kr – 10.4 yr half-life
Rb	Measurable traces, less than 1% remaining	5×10^{-9}%	—
Sr	Measurable traces, less than 10% remaining	—	—
^{90}Sr (Now ^{90}Zr)[c]	Small migration, most decayed in place	31.2%	At 1000 yr–2.5×10^{-9}% of the ten-year amount (curies) remains. 28 yr half-life
Zr	Redistributed, mostly in place	5×10^{-4}%	—
Nb	Mostly retained	2×10^{-4}%	^{93m}Nb–3.7 yr half-life
Mo[d]	90% missing	—	—
^{99}Tc (Now ^{99}Ru)	Redistributed, migrated as Tc	4×10^{-3}%	—
Ru	Large fraction retained, redistributed	0.28%	—
Pd,Ag	Mostly retained	8×10^{-5}%	—
Cd	90% missing	2×10^{-3}%	^{113m}Cd–14 yr half-life
Te	Mostly retained	0.07%	^{125m}Te–58 yr half-life

TABLE 5 (cont.)

MIGRATION OF FISSION PRODUCTS AND ACTINIDES IN THE "ZONE 2" REACTOR AT THE OKLO MINE, ELEMENT AND MIGRATION BEHAVIOR COMPILED BY E.A. BRYANT ET AL.

Element	Migration Behavior	Percent Left After [10 years][a]	Other Important Characteristics[b]
I[c]	Mostly gone	$1 \times 10^{-5}\%$	—
Xe	Measurable traces, 0.01 to 1% remaining	-0	Xenon–longest half-life = 36.4 days
Cs[c]	Measurable traces (as Ba), mostly missing	44.7%	At *1000 yrs*–Percentages of 10 yr amounts (curies) remaining listed below: ^{134}Cs–2.19 yr half-life, @ 1000 yr = 0.0% ^{135}Cs–2×10^6 yr half-life, @ 1000 yr = 100.% ^{137}Cs–30 yr half-life, @ 1000 yr = $1.2 \times 10^{-8}\%$ Total Cs + ^{137m}Ba = $1.6 \times 10^{-4}\%$ Compared to initial [10 yr] amount
Ba	Obscured by natural but mostly gone		
Ce, Nd, Sm, Gd	Very little migration	0.38%	
Pb	Redistributed, ~⅔ missing from core	4×10^{-6} (total Pb)	

^{232}Th (^{236}U, ^{240}Pu)	Mostly retained	18.5%	Containment of these nuclides and chemical identity assumptions with different isotopes in brackets reveals excellent evidence for containment of hazardous, long-lived radionuclides
^{209}Bi (^{237}Np, ^{241}Pu)	Mostly retained		
^{235}U (^{239}Pu)	No ^{239}Pu separation from ^{238}U		
U	Probably no major migration, some redistribution, (see text)		
		$\Sigma = 96.7\%$[e]	

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[a] The percentage of radionuclides (curies) compared to the total amount remaining in unprocessed nuclear waste 10 years after removal from a reactor. Data was provided by ORIGEN Program.[64]

[b] Concerns only those isotopes recognized as being a radiogenic hazard 10 years after nuclear fuel confinement, e.g., 1 μCi (microcurie) or greater via ORIGEN program for 1 MW_e of industrial energy production per year and those that have shown significant release at Oklo.

[c] Environmental questions in effective waste disposal, designated by Oklo.

[d] Nb decay product.

[e] If ^{126}Sn, ^{125}Sb, ^{126m}Sb and ^{126}Sb (0.17%), ^{147}Pm (1.99%), and ^{154}Eu (1.17%) were included, this summation would equal 100%. Unlikely to be released, due to high insolubilities, and a very large retardation factor for Eu.[65]

NOTE: The standard chemical symbols are used for elements, i.e.: Kr (krypton), Rb (rubidium), Sr (strontium), Zr (zirconium), Nb (niobium), Mo (molybdenum), Tc (technetium), Ru (ruthenium), Pd (palladium), Ag (silver), Cd (cadmium), Te (tellurium), I (iodine), Xe (xenon), Cs (cesium), Ba (barium), Ce (cerium), Nd (neodymium), Sm (samarium), Gd (gadolinium), Pb (lead), Th (thorium), U (uranium), Pu (plutonium), Bi (bismuth), Np (neptunium), Sn (tin), Sb (antimony), Pm (promethium), and Eu (europium).

V. Evaluating the Risks of Hazardous Chemical and Nuclear Waste

Risk Assessment

A large number of health effects such as acute toxicity, birth defects, temporary toxicity, and human cancer can be induced by chemical exposure. At this time, cancer is the most feared. Given our present knowledge, even if we could calculate the exact amounts of hazardous compounds that would be received by a population per given sample of hazardous waste after waste treatment and release, we would still have other uncertainties in estimating the resultant health effects. This is particularly true in the case of hazardous chemicals. By 1978, for example, only 26 chemicals had been shown to have carcinogenic effects in humans: aflatoxins, 4-aminobiphenyl, arsenic compounds, asbestos, auramine, benzene, benzidine, bis-chloromethyl ether, calcium oxide, chloramphenicol, chromium, cyclophosphamide, diethyl stilbestrol, hematite (mining), isopropyl oil, melphalan, mustard gas, 2-napthylamine, nickel (nickel refining), *N*, *N*-bis(2-chloroethyl)– 2-napthylamine, oxymetholone, phenacetin, phenytoin, "soot, tars, and oils," vinyl chloride, and "another unknown."[67] Approximately 56 more have been cited as possibilities where less definite epidemiological data exists. Hence, we are stuck with extrapolating human effects from animal data or even bacterial data, as with the Ames mutagenicity test.[68]

Dr. E. A. Crouch has plotted carcinogenic potencies of various chemicals obtained from data taken from one genetic or sexual set of laboratory mice or rats against others, where data was collected in an identical fashion, and also against human epidemiological data.[69] A 1:1 correlation fits remarkably well – even with man, if the dose is calculated in mg of chemical given per kg of organism per lifetime. The scatter of data points about the correlation line, however, is approximately a factor of 10 when responses of different rodents are compared. This becomes slightly higher when the correlation is between a rodent and man. Even where excellent animal data has been collected for chemicals, we have this additional degree of uncertainty in accurately estimating what human risks might be. With

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[67] T. H. Maugh II, "Chemical Carcinogens: How Dangerous are Low Doses," *Science* 202 (October 6, 1978):37.

[68] J. McCann, et al., "Detection of Carcinogens as Mutagens in the Salmonella/microsome test: Assay of 300 Chemicals," *Proceedings of the National Academy of Sciences* 78, no. 12 (December 1975):5135.

[69] E. A. Crouch and R. Wilson, "Interspecies Comparison."

radiation exposure, the problem is a little better defined. A large amount of epidemiologic data is compiled in the BEIR Report of 1980.[70]

An additional uncertainty in estimating the potential effects of a low dose of environmental pollution encounters has to do with extrapolation from high-dose human, epidemiologic data or high-dose animal, toxicity data, to lower doses found in the environment. It is generally made with a simple, linear dose-response relationship. However, this type of estimate could predict expected numbers of cancer that are either too low or too high compared to real effects. For example, it could be that every individual would be deactivating, or thoroughly unresponsive to, a given toxin up to a threshold amount, hence, no excess cases over the background. In the case of selenium, low levels are thought to be quite helpful to one's health. Low-level Se-containing pills are even for sale in health food stores. High levels of selenious and selenic acid are known to be carcinogenic, nonetheless. Many other transition metals which are toxic at high levels are known to be required for life at very low levels as well.

On the other hand, lower doses could give a higher dose response than expected from a linear correlation. This might be due to induction of a partially deactivating biochemical response at high levels, leading to more damage at low to moderate doses, or it could be explained by saturation of one set of pre-carcinogen processing enzymes at these levels. At least one case of this type of response has been observed – with nitrite.[71] In general, however, the data accumulated so far indicates that the linear dose-response relationship would now be about the best to use for an estimate.

Not only do we have the problem of low dose adding to risk uncertainty compiled so far, we have additional problems with time-dependence of exposure. For example: Is the individual who receives a concentrated dose for a short time subjected to the same increase in the probability of cancer as another individual who is exposed to low-level doses for a long time, but has the same cumulative dose?

According to Boutwell, *cancer initiation* is thought to occur through triggering an error-prone DNA repair system and is *irreversible*.[72] In one experiment, two groups of mice were initiated with 25 mg of

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[70] BEIR Committee, NAS, *The Effects on Population of Exposure to Low Levels of Ionizing Radiation*, 1980.

[71] Cf. P. Newberne, "Nitrite Promotes Lymphoma, Incidence in Rats," *Science* 204 (June 8, 1979):1079.

[72] Cf. R. K. Boutwell, "Some Biological Aspects of Skin Carcinogenesis," *Progress in Experimental Tumor Research* 4 (1964):207.

DMBA (dimethylbenzanthracene) per mouse. One group was promoted with croton oil for 16 weeks, starting one week after initiation. The other group received the same dose of croton oil, but the first application of promoter was delayed 16 weeks after initiation. Almost identical responses in terms of papillomas per mouse and tumor incidence per mouse can be seen for both of these groups. This demonstrates that for benzanthracene, the dose-response is irreversible, which could imply that the cumulative dose is the one that counts.

Bernard Cohen, however, has discussed studies showing that high dose rates of x-rays and gamma rays in animals are more carcinogenic than low-dose rates.[73] This demonstrates that with this type of radiation, a high-level dose delivered very rapidly is much more dangerous than the same cumulative dose delivered at low levels over a long time.

With tumor promoters, however, results have been quite different. In an experiment where all mice were initiated with 75 micrograms of dimethyl benzanthracene, and twelve 125-microgram doses of croton oil were applied weekly, 45 percent came down with tumors. When 12 identical doses were applied on identically initiated mice at two-week intervals, only 39 percent developed tumors. When applications of the 12 identical promoter doses were extended to four-week intervals, no tumors developed.[74] This demonstrates that cellular alterations *promoted* by this type of chemical reaction are *reversible.*

In addition, greater than additive risks have been found associated with drinking alcoholic beverages and smoking at the same time.[75] Other than additive responses may well be found with other hazardous chemical mixtures. Cancer induction by radiation and smoking has shown to be age-dependent as well, especially at high doses. This information suggests that quite a bit of uncertainty exists in determining what the actual risks might be; especially when other uncertainties such as the amounts of waste generated, methods of disposal, and fate-persistence are included.

Evaluating the total amounts of risk associated with hazardous chemical waste and nuclear waste by increasingly accurate methods could be quite helpful in determining which one represents the worst

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[73] Cf. B. L. Cohen, "The Cancer Risk from Low Level Radiation," *Health Physics* 39 (1981):659.

[74] R. K. Boutwell, "Skin Carcinogenesis."

[75] J. Higginson, "Environmental Carcinogenesis: Misconceptions," IPH Seminar, Harvard University, March 5, 1979.

problem. At this stage, particularly with hazardous chemical wastes, we are just beginning to accurately determine what the potential effects might be.

Implications Given by Selected Cases of Hazardous Waste

In the preceding sections, we found that the *quantity* of nuclear waste is markedly smaller than the *quantity* of hazardous chemical waste; but some wastes are more hazardous than others, and the high-level nuclear waste has a specific hazard (hazard-per-unit weight) which is greater than that of toxic chemical wastes. We might consider a hazard index equal to the product of the quantity and the specific hazard. While this is well known for nuclear waste, we found that the specific hazard for chemical waste is little known.

Moreover, the nature of chemical waste is changing. As public and regulatory attention has been directed to the waste problem, the cost of waste disposal has increased, and it may now be both cost-effective and a better public relations policy for an industry to reduce quantities of waste by concentration. But it is likely that most of the chemical waste in the future will have a much higher specific hazard than in the past.

In addition to the Love Canal and Oklo cases, there are several other examples of waste disposal problems that have implications for waste disposal issues. First, let's consider acrylonitrile. This is a base material for a variety of acrylic products. It is highly toxic and the allowed exposure level for workers has been reduced from 20 ppm to 2 ppm. It has been found to be carcinogenic in rats.[76] What should we do with acrylonitrile-contaminated waste? Burn it? Chemically break it down? Expose it to sunlight (ultraviolet)? Bury it? Put it in a "secure" landfill? Or, dump it in the oceans? At the present time a large amount of the waste has been buried in abandoned mines. This probably ensures that it remains out of the environment for a number of years, although the burial place is certainly *not* as secure as that proposed for nuclear waste.

A second example pertains to nuclear waste. Here a proposal has been made to keep it out of the environment either by a continuously monitored storage (sometimes called temporary storage, although it could be permanent if we wish) or by burial (sometimes called permanent disposal). The DOE arrangements guarantee containment within a waste canister disposal site for 1,000 years,[77] after which the degree of confidence might decrease to some extent.

[76] Personal communication, Dr. Jessie Norris, Dow Chemical Co.

[77] DOE-NRC, *Storage and Disposal.*

In this case, it is not molecular-structural changes that reduce or increase the toxicity; instead, radioactive decay ensures that the toxicity of nuclear waste diminishes considerably with time. Hence, removal from the environment even for a limited time accomplishes a useful purpose of reducing the hazard. It has also been suggested that after a few hundred years disposal of nuclear waste in the deep oceans can *reliably* reduce the risk to acceptable values.[78]

A third example, hopefully rare, is what occurs when we merely put corn and nut products in a rubbish pile. They grow a mold, *Aspergillus flavus parasiticus,* which produces the highly toxic and carcinogenic mycotoxin-aflatoxin B1. It was the untimely death of farm animals that had eaten from a rubbish pile that led to the discovery of aflatoxin B1 – one of the most potent carcinogens known. In this example, comparatively innocuous materials put on a waste pile became highly toxic by natural biochemical reactions.

As a fourth example, we refer to a study by Cohen of the way in which natural cadmium, normally in the ground, will enter the environment.[79] Assuming that cadmium is carcinogenic with a proportional dose-response relationship, one year of coal burning in the United States would eventually cause 20,000 fatal cancers. Similar numbers could be derived from a number of other pollutants. The cadmium is released to the environment either by burning coal, or more simply by bringing it to the surface in the mining process. The quantities of material (approximately 10^9 metric tonnes are generated in the U.S. annually) are so great that no secure waste disposal process that we discuss here is likely to be implemented in all cases. Much of this waste becomes widely spread into our environment with time. If there is a threshold for cadmium toxicity and carcinogenicity, then the calculated effect would be close to zero, since the cadmium is widely dispersed. We must be cautious, however, in using this example to ridicule the general assumptions of a proportional dose-response relationship with no threshold. First, it is conceivable that this large number is correct. Second, it is likely that metals (e.g., Cd, As, Se) behave differently from hydrocarbons in methods of cancer induction, and that the former set could exhibit a threshold and the latter may not. Third, we must remember that there is a lot of cancer around (18 percent of all deaths), and the addition of a small amount of carcinogen to a large pool of similarly acting carcinogens could pro-

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[78] B. L. Cohen, "Ocean Dumping."

[79] B. L. Cohen, "Consequences of a Linear, No Threshold Dose-Response Relationship for Chemical Carcinogens," *Journal of Risk Analysis* 1, no. 4 (1981).

duce a differential effect (proportional to added dose) even if thresholds exist. Therefore, without minimizing the importance of Cohen's instructive example, we question its generality.

There is also the problem of production and disposal of certain "phenoxy compounds." They have a variety of uses, including phenoxy herbicides (2-4-5T) and can be intermediates in the cosmetic industry. Although 2-4-5T is toxic and possibly weakly carcinogenic itself, the main problem arises because traces of a very toxic and carcinogenic chemical by-product are associated with it: 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD), usually referred to as dioxin. *Herbicides have been manufactured in the past* (Agent Orange of the Vietnam War) containing 150 parts per million of dioxin, although more recently the figure has been as low as 20 parts per billion. In a well-known accident at Seveso, Italy, significant amounts of TCDD were unintentionally generated and released, leading to serious human health problems downwind. Dioxin appears as the product of a number of combustion processes.

TCDD poses a lot of questions, and at this stage, we have very little information for defining the long-term problems with this chemical. At least some information is available concerning its fate and persistence in the environment.[80] It breaks down when exposed to U.V. in methanol, benzene, Esteron, and Agent Orange solutions, but is stable to U.V. when exposed directly or suspended in pure aqueous solutions by itself. Photolysis in surfactant modified aqueous solutions has been demonstrated, and this has some possibility of being developed into a treatment process.

TCDD also accumulates in fatty tissues, and bioaccumulation and concentration have been observed in ecological food chains. It is strongly adsorbed to suspended organic particulates in aqueous systems and to soil materials. Although it is generated at moderate incineration temperatures, high temperatures would undoubtedly decompose it. A detailed investigation of the chemical nature of degradation products generated by anaerobic bacterial metabolism, U.V. photolysis, or special high-temperatures incineration has yet to be done, particularly in relation to the possibility of toxic and carcinogenic effects.[81]

It seems that there are a number of questions to be answered before we can be secure in our ability to handle materials such as TCDD. One of the key issues that we are dealing with is the time of persis-

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[80] M. A. Callahan, et al., *129 Priority Pollutants*.

[81] Ibid.

tence of hazardous chemical wastes versus nuclear wastes. Hazardous chemical waste metals such as cadmium will be stable for the lifetime of this planet. With nuclear waste, on the other hand, radioactive decay greatly decreases toxicity with time.

VI. Conclusion

Adopting a waste-treatment approach in comparing hazardous chemical and nuclear wastes appears to have a greater degree of certainty in being able to discern which type of waste is worse, compared to estimating expected cancer risks for all types of hazardous waste over time. If the volumes of waste are low, laboratory and field experiments can be performed to demonstrate low leakage. If the volumes of waste are high, laboratory experiments are too far removed from the real world. We already have far larger volumes of hazardous chemical waste than high-level nuclear waste. The sealing properties of stainless steel canisters and retention properties of bentonite-mix sealing mixtures, the geologic surveillance of preliminary burial sites and depth of burial, the costs currently being sustained for effective nuclear waste disposal planning, the decision as to when burial will start (about 20 years from now), plus the historical evidence of retention of nearly all the long-lived isotopes at Oklo give straightforward information for current nuclear waste disposal plans. When comparing these parameters to the number of hazardous chemicals generated, the amounts, the current methods used for disposal, and what happened at Love Canal, we can suggest that hazardous chemical waste represents the greater problem.

We believe that many of the presently used waste disposal procedures may be inadequate in the long run. We are reasonably content that the correct questions are being asked about nuclear waste disposal, but the perplexing questions about chemical waste disposal are only now being asked – and even now, only rarely. In addition, there are as yet *no good answers*. For these reasons, we believe that hazardous chemical wastes may pose many future problems for society, while acceptable solutions are clearly in sight for high-level nuclear waste.

Finally, we think that the comparisons made in this paper will help the American people understand the problems and the decisions that are faced by government agencies and the voters. It would help if the news media would present such comparisons.