Physics looks at waste management

What are the best ways to find out what is in our waste, sort and separate it, return to service any parts that can be used again and properly dispose of the remainder?

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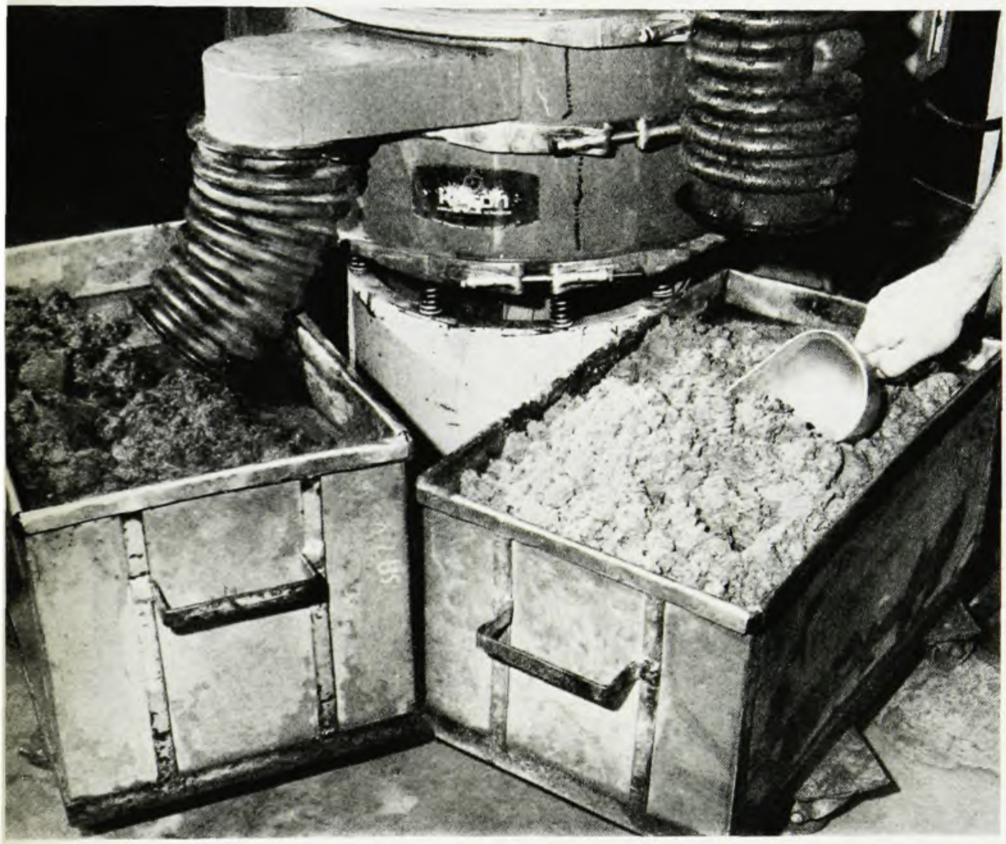

Electromagnetic separator for light and dark glass granules salvaged from the unburned ashes of a municipal garbage incinerator. Dark glass (left) is separated from the uncolored glass (right) by differences in magnetic susceptibility. (Photo by UPI from the US Bureau of Mines Solid Waste Center.) Figure 1

The question of what role physics plays in the garbage business invites the casual answer: "Not much." But that would be wrong, and not from any trivial viewpoint, such as the mechanics of garbage grinders. Admittedly, physics does not play the key role, and certainly what is known colloquially as "high physics" may be quite unresponsive to the problem. Nevertheless, the ethos of physics and recognizable physical principles have become peculiarly useful as part of the intellectual armamentarium of waste management. Surely we are biased—two of us are former physicists and one is a former physical metallurgist. We will try to convince you that we are serious and have a valid point of view.

First, we point out that modern high-consumption society operates by using energy to turn resources into junk; we derive comfort, pleasure, and other temporary benefits through intermediate stages of this dynamic process. Of this trio—resources, energy, and junk—the first two have received some organized attention, albeit woefully inadequate, as recent reconsideration shows. But the last one has been generally ignored until very recently (see, for example, the Solid Waste Disposal Act of 1965, as amended by the Resource Recovery Act of 1970): Throw it away, there's lots more room, and lots more resources where those came from. All this now changes.

What is waste? Our view will become obvious through what follows, but a good enough starting definition is: Waste is something that we have pro-

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duced, for which we find no satisfactory use. This avoids pejorative prejudgments about pollution and so forth; we will talk about pollution later on, but do not wish to becloud the view *ab initio.* The point is important; take, for example, the one-way beer bottle, a topic of frequent environmental opprobrium. Is it a problem of pollution, of resource conservation, or of what? Now it is a fact that if everyone on this earth drank beer to insobriety, tossed away the empties, and persevered at this forever, geologic processes would turn the empties back to sand before we ran out of it for making more bottles. The bottle is quite acceptable for sanitary landfill, and the energy required to make a new one is not very large. Thus, the glass container represents more closely a problem of convenient disposal and litter prevention (perhaps to be solved by recycle) than one of material resource conservation.

We will choose here not to emphasize the nonmaterial (aetherial) wastes such as unwanted heat, electromagnetic radiation and sound. Rather, we will emphasize material wastes, and stress how some physical principles can be constructively applied.

These wastes come in many categories that cannot be arranged in order; they range from high-volume low-cost things (mine-tailings or paper) all the way to the opposite extreme of low-volume high-cost (mercury in switches, for example). But they can also be categorized as disposal problems (mine tailings), steady-state management of renewable resources (paper), global scarcity of nonrenewable resources (mercury, tungsten, phosphorus, and so on), and hazards (untreated sewerage, most heavy metals, pesticides, for example).

In the narrowest sense, waste management involves sensing what is there, sorting, separating and/or transforming, returning to service what can be useful, and properly disposing of what is left. In those steps lies a great deal of physical and physics understanding, and even these steps do not reach all we wish to get at.

One example of the way physics can get involved is the electromagnetic glass separator shown in figure 1.

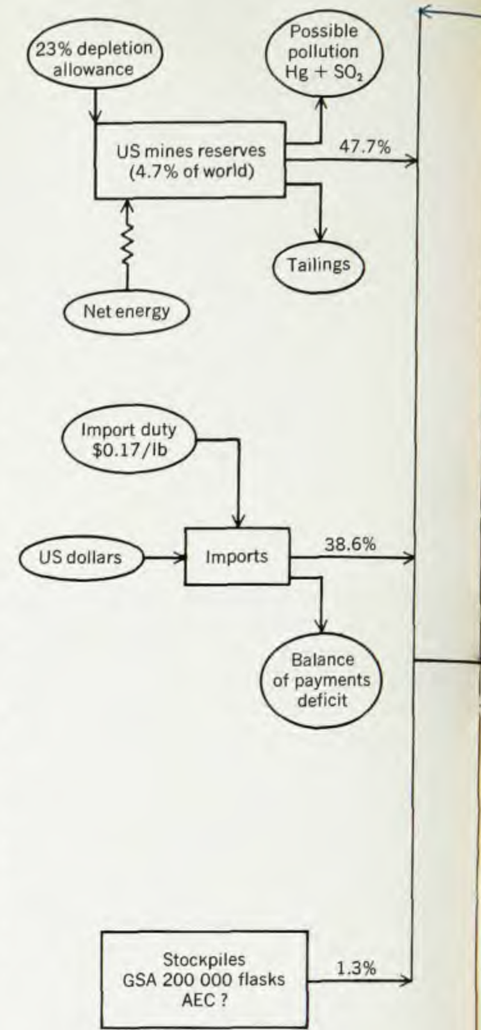
We have observed a striking feature in all this recent environmental and sociotechnological activity—waste management, resource conservation, energy, pollution and so forth; it is the disproportionately large fraction of new practitioners who come from the physical sciences, particularly from physics. We have wondered why this is so. Is some quality involved, not always recognized as valuable—in spite of what we said of physics at the very beginning? The cynic might cite money, thinking of the drying-up of physics research funds. That doesn't hold, for the new practitioners were usually quite competent in their old trade, and would have had little difficulty in pursuing it. Perhaps it is a penchant for modeling—looking for the big and little things, with orders of magnitude assigned, followed by selective analysis of what appear to be the bigger parts. Perhaps, more sharply, it lies in the difference between physics *per se* and the process of solving physical problems; some physicists delight in the former and others in the latter, which is in truth a very interdisciplinary activity. Environmentally related problems need a lot of such interdisciplinary thinking. He who neglects the connection between paper recycling and private investments in the southern pine forests is spiritual brother to he who neglects the plasma potential in his ion source.

The objective, and two principles

The objective of proper waste management can be stated easily; it is to achieve a socially optimum mass or resource flow. However, the easiness deceives, and what follows makes a sort of extended definition, with both normative and deterministic components. By deterministic components we mean more-or-less immutable facts (such as so much sewage creates so much oxygen demand of effluent water), and our developing scientific and technological knowledge related to handling materials. We will concern ourselves here mainly with these latter parts. The normative decision of what is socially optimal depends upon the determinable facts, but only in part. Styles change from time to time; we are witnessing such a change now.

Many scientific and technological tools get used; perhaps an early nontrivial example will help. Figure 2 shows a fairly simple and almost self-explanatory flow chart of mercury through our 1970 US civilization. The need for several skills appears quite plainly; for example:

- The need for, and power of, overall modeling techniques. "Everything goes somewhere," as Barry Commoner says in connection with these matters; the tracing out of "where" identifies (for instance) the large use of mercury by caustic-chlorine plants (where it is used as a circulating electrode), and the (hitherto) substantial leakage of mercury into rivers and lakes. Working flow charts for most materials are much more complex than figure 2, but the power of this sort of mass-flow modeling is immediately evident.
- The need for much analytic detective work. The actual mass of mercury is very small compared to the mass of environment into which it is wasted: Five parts in 10^9 is a significant concentration in drinking water. Measuring such things easily, cheaply and ubiquitously demands sometimes the most artful application of mature science (mercury by neutron activation analysis, for example) and ingenious application of new techniques. In many situations it does not suffice to identify and quantify atomic components of wastes; their chemical and physical forms must be found, and also their proclivity to



The flow of mercury through society. This is a schematic representation of mercury flow in the US economy during 1970. Ovals represent "externalities" (inputs and outputs), and colored lines show recycle paths. Figure 2

change (for example, metallic mercury into methyl-mercury). We think of the relatively new technique of photoelectron spectroscopy[1] in this vein, because it allows determining in many instances not only the element but its valence state (say, sulfur as SO_2 and as SO_3).

▸ Chemistry, physics, regional modeling, and so on do not appear very recognizably as separate activities here. They are tools, not ends in themselves. Here is a big difference, sometimes a stumbling block, in the understanding of what is to be done: We see here not physics for its own sake, but for a problem's sake. Thinking must be problem-oriented, not discipline oriented; the former is "real," in the sense that it exists apart from any artificial categorization we may make into particular disciplines.

▸ The social-scientific and normative inputs are very real. Mining subsidies in figure 2 come via societal decisions; they tend to lower the price of virgin metal and hence encourage waste and discourage recycle. Many of the pollution lawsuits in figure 2 are brought by sport fishermen and resort operators. To discover the normative content there, try placating the intrepid angler by offering him an even larger edible frozen fish in return for his inedible mercury-tainted catch.

Thus we see a general mass-flow objective, and many scientific-technological tools that may help us to accomplish the objective. Are there useful guiding principles? We see two related to our scientific side of these discussions. The first is conservation of mass, a point already mentioned and obvious, but often strangely neglected. Indeed, everything *does* go somewhere. Sometimes the fact is inconsequential, as one more bucket of water is assimilated into the ocean. But for some materials the natural capacity to assimilate wastes is remarkable small, or the wastes are reconcentrated by natural processes, or there is only so much available. We shall see examples of all these things later.

The second principle is more subtle, and we have found some difficulty even in describing it to ourselves. We call it "the principle of minimum-energy paths." By this we mean that in taking a substance from some first state to a desired second state, we prefer processes involving the least total exchange of energy. Violating this principle generally means either the appearance of an inappropriate energy cost, or a concomitant capitalization charge, or use of additional material (hence new waste), or some combination of all these things. As a seemingly frivolous example, but a harbinger of later discussions, we separate nails from broken glass with a magnet, not with a mass spectrograph. Anyone who has explored the path cows take uphill will understand what we mean: They take the least slope, with never an unnecessary descent to be paid for later. This principle has the flavor of being restatable in terms of minimum entropy increase for the material process, but we have not explored it very much.

Continuing such an extended discussion of guiding principles leads us to figure 3, which is really a simple outline of what follows in this article.

We recognize that the idea of societally optimum mass flows can be restated in terms of three easily recognizable societal aims:

(a) Pollution control

(b) Conservation of concentrated materials

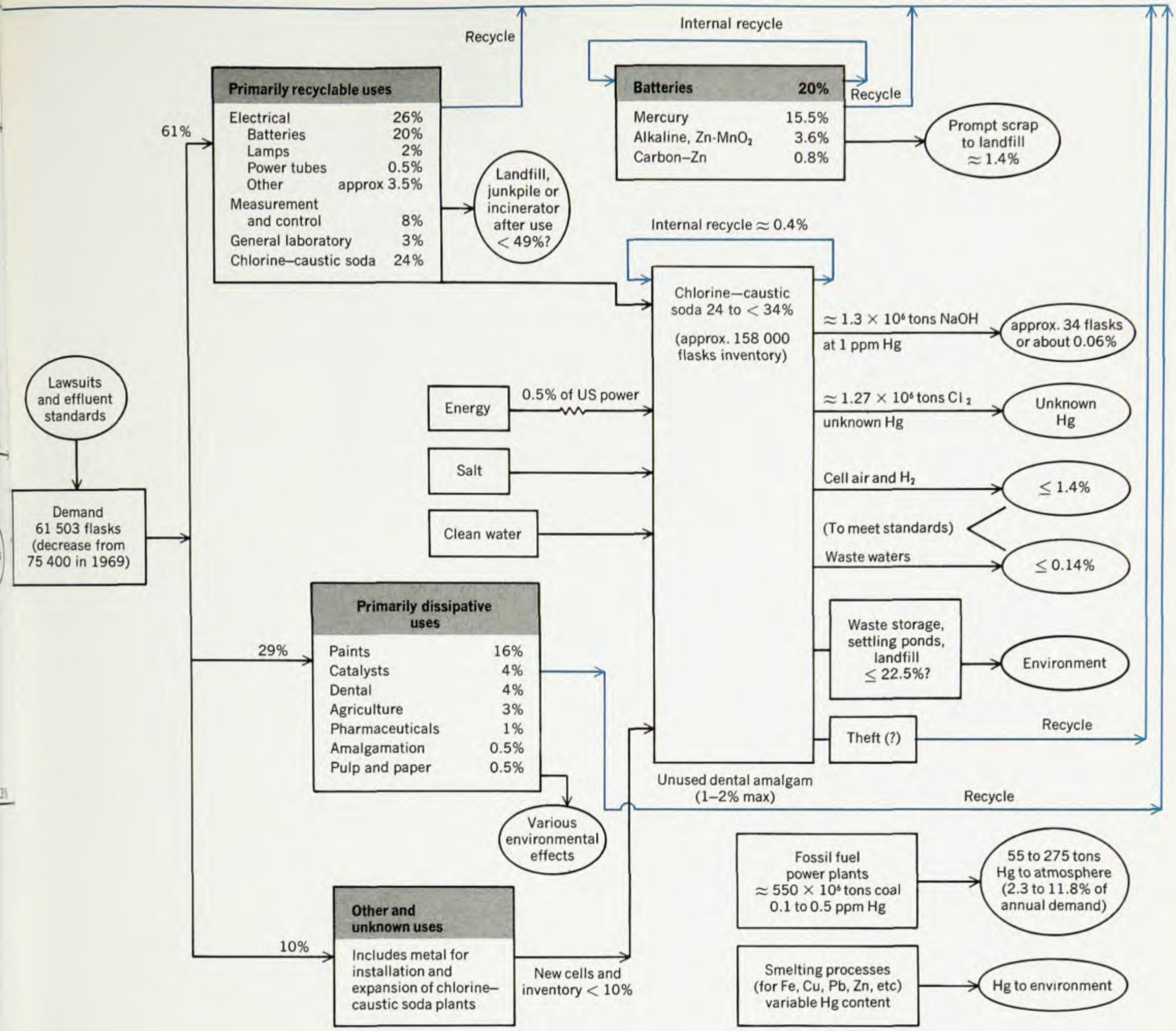
(c) Material wealth

These are to some extent in conflict, particularly the last with the other two. The question about the proper balance between them brings in normative judgments; the decision is basically political, not scientific, as almost everyone will probably agree. It is not economic either, a point less readily accepted: The aims (a) and (b) above are largely external to the market system of self-regulating management. It seems to us that the US is now shifting from (c) to (a). Note that the first two items, pollution control and conservation, are frequently related; this is not always so, as later examples will show.

Our article is about things at the left side of figure 3. Although all three general strategies abide in our societal decisions, and all three enter some of what follows, we will finally concentrate on pollution-control strategies. Thus, below that heading are the seven particular strategies that we envision and will describe in detail later.

Before turning to those matters, we will linger to discuss the interactions among material conservation, material utilization, and energy cost from one point of view. Figure 4 shows on the horizontal axis increasing degrees of material concentration. At the left is matter in its most dispersed state, averaged over the earth's crust at what is known as the "Clarke" level;[2] depending upon the material in question, the relative abundance might be parts per million. Usually we utilize ores or other natural concentrates, at a higher level of natural organization, and process them to produce components and useful relatively pure materials. By this we have in mind iron and steel, glass, neoprene, doorknobs, and the like. This degree of "purity" is the highest in our society, and appears at the right side of the figure.

The systems we build as end products in society lie to the left of components. The intellectual organization is higher, but it represents a planned dispersion of components or refined materials: Nails, boards, glass, iron pipe and doorknobs are mixed up in carefully defined ways to build a house.



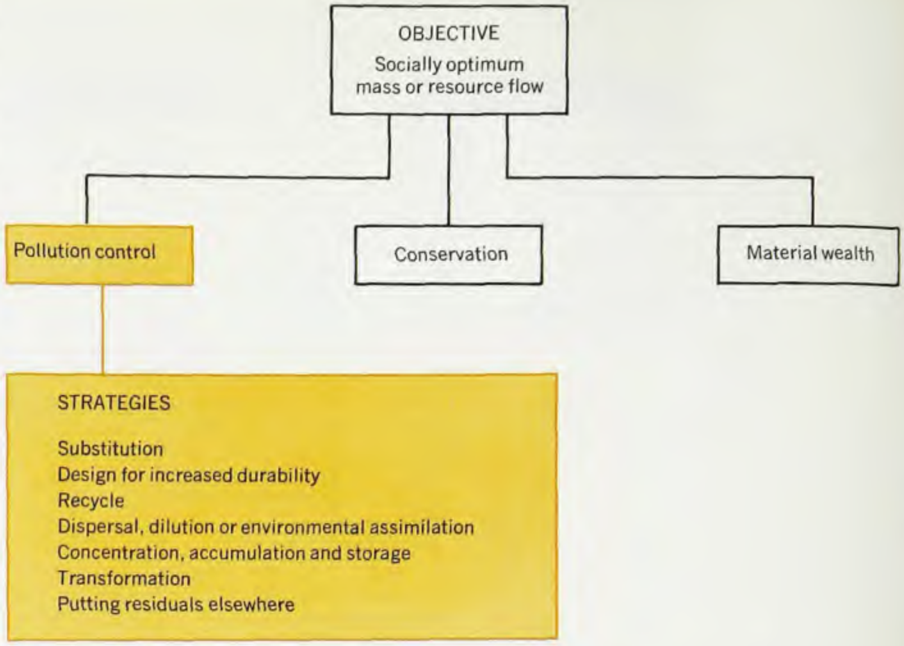
Off to the side of lower concentration, but usually higher than "ores," lie the mixed wastes that society produces: sanitary land-fill dumps, for instance. The somewhat overlapping range and nature of wastes and ores is illustrated by our occasional discussions about, and forays into, "mining our wastes" for essentially new materials.

Complicated interchanges occur among these states of concentration, and we show several of them on the figure. Start, for example, with "ores," a general term that here could include such things as forests. We mine (or cut down), smelt (or saw up) and form nails, boards, and so on. All this takes energy, and the arrow labeled "conventional mining" makes a loop of size roughly coordinated with the energy expenditure involved. This extraction from "ores" usually expends more energy (or its equivalent cost in other materials) than the alternative processes of extracting the same thing from society's mixed wastes. Thus the loop called "mining our wastes" usually represents a smaller energy per extracted unit. But that option has not yet been much exploited, partly because ore bodies are usually much larger than waste bodies (dumps). Hence economies of scale favor mining natural ores. Other considerations enter too: depletion allowances, material homogeneity, historical custom, differential transportation rates, less pollution, and so on. Even more costly in energy, but always available as an option, are processes for extracting needed materials from the natural average abundance in the earth's crust.

So much for making components. These are assembled, usually at modest energy cost, into the systems (houses, refrigerators, . . .) we use and consume. These may be repaired (a similar arrow, but most thrifty of all), and sooner or later discarded as waste—an inexpensive process in itself, but often expensive to recover from. Each higher stage of "organization," as distinct from mere concentration, as shown in the figure usually requires additional processing energy. Perversely, returning junked goods down the ladder (shredding cars) also usually requires energy. Wastage of goods tends generally to disperse material toward the Clarke limit, which leads to pollution if the task is not artfully accomplished, and also leads to requirements for more "ores."

From these admittedly ethereal deliberations comes the operating principle that, unless other factors supervene, we opt for the smallest loops in any generalized figure 4. That is, we elect not just individual processes that tend to be energy conserving, but search for whole options that minimize total energy costs along the entire path of ores-materials-goods-wastes. Consonant with this, we aim for relatively "shallow" recycling, as a rule, both from conservation and minimum-energy points of view. On the other hand, pollution control and material conservation are occasionally at odds, a fact we mentioned earlier. For example, the prospective pollution-abatement schemes for automobiles require more equipment and (possibly) precious platinum for catalysts, a lower engine ratio, and other changes that (in general) require higher fuel consumption and capital investment for the same horsepower output. The effluent is relatively benign, but there is more of it; thus in this case we achieve pollution control at the cost of additional resources.

Before some action decision can properly be made, the various possible strategies must be worked out so that their merits can be compared. Quite a few strategies appear, each with technological, social, scientific and normative components. Limiting ourselves even more, we will consider chiefly the technologist's approach,[3] but caution the reader to bear in mind the partial view. Here now follow seven schemes that can be used separately or in combination, to achieve optimum mass flow relative to the aim of pollution control. The first two—substitution and durability—apply "before the event" of waste production; the latter five deal more directly with waste management.



Technological strategies associated with the social objective of optimum mass or resource flow. Decisions among the three main strategies are basically political, not scientific or economic. The seven strategies listed for pollution control are discussed in detail in the text. Figure 3

Substitution

Alternative use can be made either of systems or of materials. For a combination example, recall the use of mercury cells in the chlor-alkali process (figure 2 and accompanying discussion), and the resulting societal misery. These can be replaced by diaphragm cells (70% of the US chlorine is now supplied this way), albeit by forfeiting some quality in the sodium hydroxide product. This substitution of processes is what our Oak Ridge colleague, Hal Goeller, calls "functional substitution."

Materials themselves can be substituted, often in simple ways. Copper is a detrimental impurity in many steels because it reduces formability; thus copper wiring in automobiles makes recycling old automobiles more difficult. Aluminum presents some problems, but not as many; then why not install aluminum wiring? One trouble is that reliable and longlasting electrical connections are harder to make with it. Here, then is a place for some ingenious idea.

Again returning to the example of figure 2, we have divided the mercury uses into approximate recyclable and dissipative categories, where the latter arises from the intrinsic nature of the use. Many of these uses *depend* on the toxic nature of mercury and its derivatives (for example, for agriculture, paints, and slimicides in the pulp and paper industry). Therefore here is a fertile field for substitution technology, to find more available (less scarce) materials that are less persistently toxic, thereby both abating pollution and conserving available resources.

Durability

If clever design of products can lead to longer useful lifetimes without increasing the difficulty of disposal of the object when it is finally junked, then waste volume is reduced without decreasing material affluence. For many products, the benefit from increased useful lifetime exceeds the cost of added quality. Yet normal economic incentive to the constructor is to maximize present profit, and sometimes even to design for maximum rate of obsolescence within the confines of customer acceptance. Thus our economy operates with a built-in bias towards a throw-away philosophy.

We feel that the durability strategy is very important, but it is one in which normative values enter strongly. How can the concept of durability as a "good" be promoted without stifling inventiveness, which can cause true (and often beneficial) obsolescence? What is the balance between the joy of new style and the concomitant waste? As a practical level, is it really necessary to design household appliances so that when something goes wrong we must junk the whole thing, because fixing it requires a part that you can't buy due to design change, or needs more skill than you can conveniently hire—or perhaps the construction was basically nonreplaceable or nonrepairable? Household appliances execute large and frequent cycles on figure 4, but that need not be so. Some people comment on this point that production, *per se*, is a "good" because it creates employment. Of course employment is good, and necessary, but such comments miss the mark of societal gain that we aim at here; surely people should do better things than create objects designed to make an early transition to junk.

Private housing makes a subtler case, and one in which we recognize three time scales of concern. The first and potentially most expensive in the long run is that of the speculative builder, for whom the house must look good only until he is well out of the involvement. The second is that of the average houseowner with a time horizon of say 20 years, who adds insulation, storm windows and maintenance, and minimizes to some extent the total societal cost during his tenure. The third time scale is that of society as a whole, and has to do with much longer-range questions such as depletion of forests and optimum land and energy use. In general, the total pollution and wasting of resources decreases as we move from the shorter to longer time scales—sometimes at the cost of less convenient or spacious accommodations, and sometimes not, but always at the sacrifice of present savings for future rewards.

Recycle

Recycling to reduce both waste and overuse of resources is a very popular topic of conversation these days, and we spend some time talking about it. Recycling comes in many degrees of sophistication; among the simplest are such arrangements as the collection of glass and newspapers at community centers. The economic incentives being not very large at present, the work proceeds, if at all, as a labor of dedication. The potential power of it, however, is large: Something like half the paper products made can in principle be recycled, and if that were done, our forest cutting could be substantially reduced. By increasing recycle, our burgeoning demand for paper products can be met for some years without depleting the quality of our most important renewable resource. Of course, some uses for paper are inherently dissipative, and all involve some degradation of quality. Therefore demand must ultimately level off if we are to manage forests at a steady state.

Our principle of minimum energy paths is nicely illustrated here. Provided extraneous factors do not interfere (for example, the use of a gallon of gasoline to deliver an armful of newspapers to the recycle center), paper, glass, aluminum and many other things are recyclable at low-energy cost—much less than required for winning new material. This method of separation by the individual is the Maxwell Demon approach to recycling, by which the entropy of mixing is defeated by the human capacity to distinguish components of the wastestream.

Aluminum makes a noteworthy example. The total coal equivalent energy to mine, beneficiate and electrolytically refine a ton of aluminum is about 56 000 kWh, taking into account all the inefficiencies but excluding transportation.[4] This works out to 60 eV/atom, but the total energy cost of remelting is only 1–2 eV/atom. In general, recycling energies are in this order: 1–10 eV. Other examples are not so extreme as that for aluminum, but energy factors of five to ten are not unusual. Also, do not forget the resource-conservation side of the story.

At the opposite end of the recycle sophistication street lies the proposed fusion torch,[5] upon which much discussion has been bestowed. Because it has figured rather prominently in some assessments both of controlled nuclear-fusion priorities and of how physics comes to the aid of waste management, let us linger to discuss it in some detail.

In briefest terms, the idea stems from the fact that most schemes for achieving controlled nuclear fusion depend upon confining an exceedingly hot plasma—at a density of 10^{14} to $10^{15}/cm^3$, and a temperature of above 10^8 K, or 10 keV—by magnetic fields alone. The confinement is at best leaky, and it is just this leakiness that makes even the scientific demonstration of controlled fusion so difficult.[6] Well then, the thought goes, if this superhot plasma keeps escaping (and we must keep re-injecting it, which is another story), can we not find some use for it? One scheme would be to use its heat value in a thermal cycle to make electricity; another would attempt the same thing *via* direct electrostatic conversion. A third scheme, and the one of interest here, is to use it as a primeval blowtorch, to ionize and reduce to the elemental state everything that is dumped into the exhaust. Unfortunately the scheme will not work, for several reasons.

The first reason involves simple materials flow: No likely fusion scheme can avoid having a substantial amount of tritium in its leakage exhaust. Thus anything introduced into the exhaust and converted to elemental states will become intimately mixed with tritium. Then for later re-use, a further separation of radioactive tritium must be made from whatever comes out of the fusion device; reducing the concentration below (say) $1:10^8$ or $1:10^9$ appears to be a worse problem than the original one.

The second reason that the fusion torch is a fundamentally poor idea involves violation of the principle of minimum-energy paths. Each ion carries with it the ionization energy, plus whatever was radiated (by excitation of incompletely stripped ions, and so on). This will be some 30–40 eV/atom at least, and probably much more, if past experience is any guide on how effective incompletely stripped atoms are in holding down fusion plasma temperatures. Remember also that this is the theoretical minimum; experience shows that complete system energy costs run several times as much. For aluminum, it is a factor of about ten. The consequences are: (a) If all this energy is not recovered with efficiency as high as if the clean plasma exhaust were dumped on a hot surface designed for maximum thermal recovery, the energy waste is huge; (b) with each recycled atom carrying so much energy on its back (so to speak), no great amount of material can be recycled. We believe it's not possible to meet requirement (a); regarding (b), we point out that with a fusion exhaust energy available of 1 kW/person (about equal to the entire US electric power generation at present), and average atomic weight of 12, the maximum amount recyclable would be 0.3 kg/person-day, if all recovery schemes were 100% efficient. This is much less than the current municipal solid waste generation of 2 to 3 kg/person-day.

The third reason why the fusion torch will not be practical has to do with recent findings about what will be the power balance in any conceivable fusion reactors. For open-ended systems (magnetic mirrors), the balance seems so precarious that for them to work at all, energy in the copious plasma exhaust must be recovered via direct electrostatic conversion, with some 90% efficiency or more; surely we cannot do that with an energy-consuming fusion torch in the way. For closed systems (Tokamaks, stellarators and toroidal devices), the amount of exhaust will (we hope) be not very large, because of better plasma confinement than was at one time feared.

All these questions beg the very practical ones of recovering whatever materials condense from such a carbon-hydrogen-oxygen-metal-etc. plasma, in usable form at low cost. Direct mass separation appears bleak, because the multiplicity of isotopes sets us to doing one atomic mass unit at a time, and even worse. At the Oak Ridge National Laboratory, where most of the US work on electromagnetic separation of isotopes is carried out, the cheapest material (iron 56) sells for \$50 000/kg.

Where does this leave us? There exists a huge middle ground of important tasks and low-energy paths to follow. For instance, the US Bureau of Mines[7] describes a scheme for separating incinerated wastes that sorts out iron, nonferrous metals, even colorless and colored glasses, at a cost of \$4.00/ton, to yield products estimated to be worth \$15/ton. Here are some more challenges for physicists: how can a waste stream "best" (for example, in terms of minimum energy, invested capital, and maintenance) be processed? Processing includes transport, probably shredding, and sensing or sorting into segregated streams for recycle and other fates. In the Bureau of Mines process the sensing and sorting steps exploit physical properties and principles. A density separation is followed by a magnetic one to remove ferrous materials, and a separation of colored and noncolored glasses is accomplished in a high-intensity magnetic field by way of differences in magnetic susceptibility (see figure 1). Extensions of schemes like this receive much deserved attention these days; the technical prognosis is excellent.

Further analysis of municipal waste management reveals some important problems that are probably far less tractable than the technical ones we have mentioned so far. Current waste-management costs are due to collection and transport (typically 6–10, or more, dollars per ton) and a smaller amount for disposal (about 1–2 dollars per ton for landfill or 3–7 dollars per ton for incineration). However, acceptable disposal sites for landfill near the cities are becoming extremely scarce and, because of growing environmental constraints, disposal costs (for example, for incineration) are increasing rapidly. One way to offset spiraling costs is to derive revenue from secondary-materials sales *via* a recycle operation. But a recycle system is capital-intensive, and economics dictate a relatively large-scale operation (typically 1000–2000 tons per day). Since this size corresponds roughly to a million people we are led to the "Wasteplex" concept[8] of bringing waste from a relatively large region to a central waste utilization and recycling complex. In eastern Tennessee such a potential region, which enjoys a low-cost transportation system (by navigable waterway) is twice the area of New Jersey. It encompasses several medium-sized cities and 29 counties in two states.

Thus the principal problem of municipal solid-waste management is two-fold: first the development of economic recycle technologies to produce *marketable* secondary materials; second the development of long-term cooperative arrangements between political jurisdictions that historically covet independence.

Dispersal

The traditional scheme—dilution as the solution to pollution—works well enough, so long as we understand how the system works and don't overload it. Dispersal is in reality a natural recycle, and the capacity for recycling many materials—even SO_2, CO, or H_2S—is huge, because huge amounts are produced, absorbed and degraded naturally. But the dilution must be carefully done: Tall stacks for SO_2 dispersal may have worked well much of the time up to now, but the effective threshold for local and even remote downwind damage has been passed in the New York City area and in much of Europe. Again, physical monitoring of the conditions and understanding the natural recycle process are things for physicists to do.

For all practical purposes, the dispersal scheme breaks down entirely for certain materials. These are particularly the toxic heavy metals, some of which can reconcentrate in the biological cycle and which are persistent and cumulative; that is, they never degrade into harmless forms. To be sure, a small amount of mercury *can* be safely dispersed; mercury occurs naturally in water at less than one part per billion, and has an average crustal abundance of 50–100 ppb. But the amount safely disposable by "dispersive" loss is so much less than the amount required to be in use by our modern society, *that no effective option exists but to recycle most of it*, or otherwise prevent it from being dispersed back into the environment.

These latter remarks touch upon a very important matter, which has limits we are not competent to judge. For millions of years, we and our evolutionary ancestors have lived in, and adjusted to, a world of certain natural concentrations, and we have little knowledge about our ability to survive (over centuries and millenia, that is) in a world of much different ones. The effects of some things we disperse now are almost wholly unknown; our ecologist and geneticist colleagues are rightly worried. This is no cry of "back to nature and damn the cost"; it is, as is the rest of this article, a plea for mature sociotechnological assessment.

Concentration, accumulation, storage

If the material cannot be disposed of any other way and is not reusable, we can collect it and store it away safely—for as long as we wish, we hope. The prime example here is radioactive wastes—they are very hard to transform into non-radioactive ones, and dangerous to leave unattended. Even though the nuclear physics of radioactivity may be well understood, the storage problem is not; physics enters here too. Should one separate the isotopes, or at least the elements, so that short-lived and long-lived residuals can be handled more expeditiously by separate schemes? The proposed program for disposing of solidified radioactive wastes in salt mines distinguished only low-level, long-lived alpha-emitters from high-level ceramicized billets of (mostly) shorter-lived materials. Whereas the main geophysical questions relating to salt beds and to the effects of the wastes on the salt deposit appear well posed and relatively well answered (in terms of geological stability, thermal effects on the salt, decay of activity in detail with time, and decay of temperature with time and position and so on), a lot more needs to be done. Even for this particular scheme, a number of further details need working out. How close together can billets be stored with safety? How close can conventional salt-mining operations be carried out? How could we recover the radioactive canisters, should something unexpected go wrong?—and so forth. Even more, a detailed assessment of the salt-mine scheme versus other storage methods (for example, elemental separation, bed rock disposal, and so on) has yet to be made. Also, while technically speaking some given method may seem preferable, we must also consider what responsibilities alternative methods may visit upon future generations.

Transformation

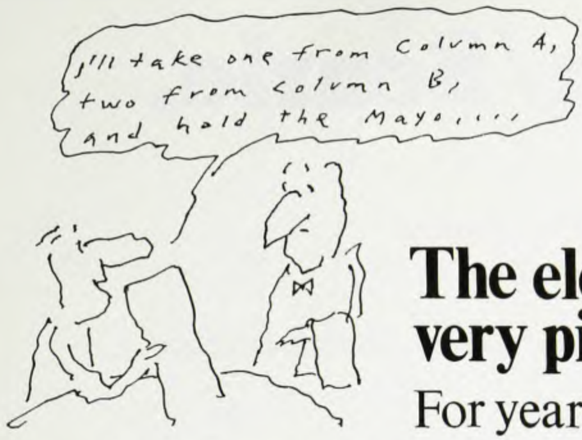
Almost too obvious for detailed comment here, yet important nonetheless, are the vast number of physical and chemical steps that can be taken to render waste materials harmless, or relatively so. "Sewage processing" is a generic term covering many examples. More esoteric, perhaps possible, and perhaps of particular interest to physicists is the idea of burning out selected radioactive wastes. It is possible to calculate that the idea of transforming *all* radioactive wastes to stable isotopes, *via* (n,γ) reactions, usually, seems not possible—more reactors (generating more wastes) are needed than we had in the first place. On the other hand, a number of the long-lived elements, which present particularly hazardous or long-term storage problems, might just be convertible this way. Separating these (most transuranium) elements also poses problems, the full measures of which have not yet been taken, as we said before. So the question is still somewhat open; typically, its resolution calls for the participation of many professions, including nuclear science and technology, chemical separation, long-term economics, projections of human behavioral trends, and those able to weigh the value of preserving future options.

Putting residuals elsewhere

An easy technological suggestion to make, but a hard one to carry out, is the idea of shooting particularly intransigent and harmful wastes (radioactive wastes for example) into the sun. Against such ideas are the hard facts that radioactive wastes and their shielding will weigh thousands of tons (but some isotope separation is possible) and that the launch into orbit cannot yet be made accident-free.

For some time now there has been a tendency for polluting industries to seek the wide-open spaces where the assimilative capacity of the environment is not so heavily burdened as it is in most urban centers. The present lively controversy over a large coal-burning electric power plant near Four Corners (of Colorado, New Mexico, Arizona and Utah) is an almost pure example. Provided the "export" is well managed, it can be a viable tool. However, overuse or misuse can lead to incremental irreversibilities. That is, a new area might stand one or two facilities but not a dozen; however, bit by bit, the dozen is reached. Inhabitants of the region may have little to say about the gradual deterioration that results. Indeed, an increasing fraction of the population becomes dependent for their livelihood on the industries, and there is little incentive for long-range planning. Presumably, national pollution standards will go a long way toward blunting this type of development. But also, one sees the need for careful regional planning that will depend on modeling (physical, biological, economic, demographic, and so on) of the air and watersheds involved. Hence the physicist becomes part of the regional planning team.

Another form of export of pollution occurs with regard to translocation of



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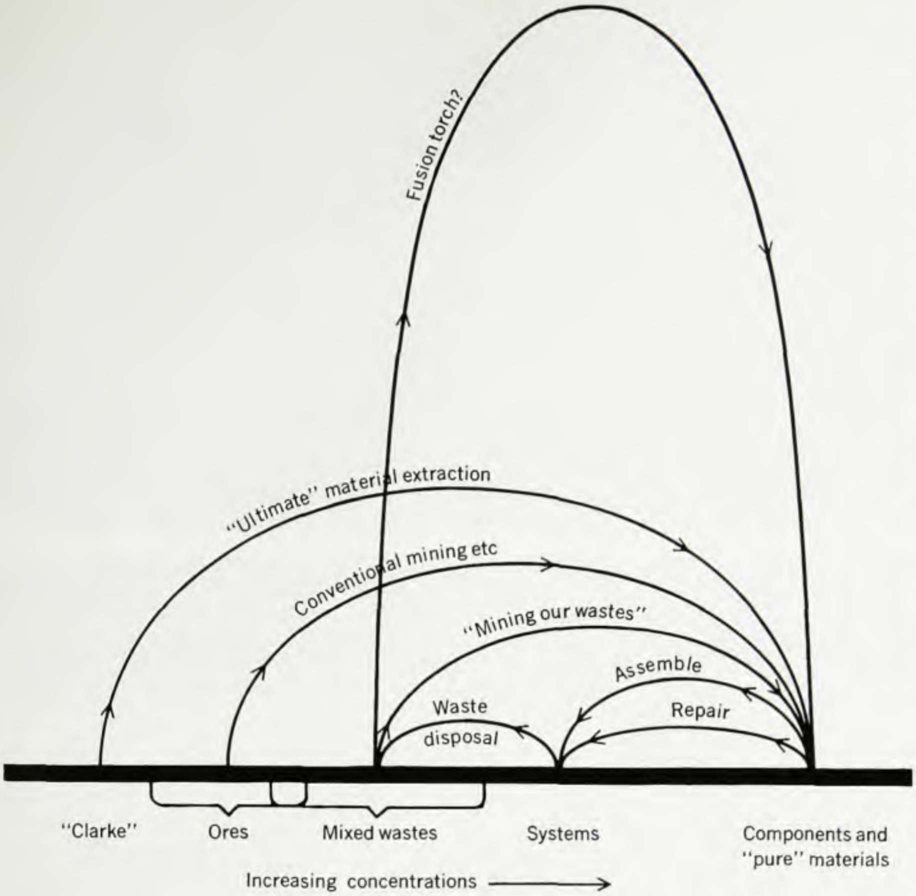

Energy commitments incurred in the processing of materials. The horizontal dimension represents increasing degrees of material concentration, from the most dispersed state (the "Clarke" level) on the left to pure materials on the right. The vertical dimension is related to energy expenditures for various processing paths. The "fusion torch" is probably not a realistic concept.
Figure 4

American enterprises, especially to the "underdeveloped" regions of the US and other countries where concern for the environment is, to date, very much secondary to economic development. Our own preaching about restoring and maintaining environmental quality may sound fine to us; we are a post-industrial society not only with the sociotechnological capability to effect the changes, but also with not many severe problems of other kinds. But to our friends in the tropical, less-developed countries, the four great killers are malnutrition, malaria, tuberculosis, and schistosomiasis. Relief from these horrors, in the minds of many, comes via the path of rapid generation of national wealth through industrial development—the very route the US has traveled—and smoke coming out of the chimney is a sign of progress. Dying at age 55 of lung cancer seems pretty remote compared with starving to death next year at age 15.

What is the answer to this "across-the-track" question? For the economically privileged to say that each sector (or community or nation) must decide for itself constitutes a pious hypocrisy, reminiscent of 19th-century social Darwinism. Such an attitude forces the disadvantaged sectors to opt for accepting residuals. Clearly, the advantaged sectors have to give quite a bit to the common cause, if they are to stay morally solvent. Besides that, we see a strong self-interest in aiding other nations in their problems. Our wastes wash to other shores, and *vice versa.* We all share the same air and water, and many recent global studies have shown both the connectivity and the urgency of realizing the global consequences.

These thoughts take us far from physics, to societal questions that we earlier promised to try to avoid; but see how central these issues are, how they help weave the fabric of our society, and how we cannot avoid them in any real discussion.

A role for physics

The physicist alone will not set the priorities among the three goals of figure 3. That is for society to determine. But he can be very influential in developing new options and in deciding between alternative strategies for getting to where society decides to go. The physicist will be called upon along with colleagues of other disciplines to tell how the environmental system works or how it can work, how the system can be measured and described quantitatively, and what the limits of human activities are within the constraints of societal goals. We have tried to demonstrate this by showing that the role of physics, or at least physical thinking, is central to assessing the alternative technological strategies, for achieving one of these societal goals—pollution abatement.

Beyond all that lies a great deal more, which we have not mentioned. For example, even after the societal choices are made and the regulations are passed, a very complex activity of monitoring our previous condition—whether it was better or worse—has been a substantial physics activity, and well recognized.

Because in all these supposedly beneficial things that we hope to see come to pass we require an increasingly complex organization of society, we must be willing to pay for it. One cost is the need for much more information about our physical environment, in ways that can be usefully interpreted by society as a whole, and not just by physical scientists. We are persuaded that physical principles, physical thinking, and, yes, physicists, play an important contributary role in achieving a more socially optimum management of our waste. But the chance for a lasting contribution hangs heavily upon the practitioner's awareness of the broad sociotechnical dimensions of the problem. To proceed otherwise invites irrelevance and justifiable criticism.

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