

DISPOSABLE PRODUCT DESIGN AND RECYCLING

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ABSTRACT

Of late, recycling has lost some of its luster, even as prices are increasing for recovered materials. First, collection costs continue to be high. Second, recycling rates seem to be leveling off. These two difficulties are related. The paper begins with an overview of the causes of these problems, concluding, as have many practitioners, that an increase in automation is required. Automation expands options for solving some of the problems, but the structure of the recycling industry, embodying a fundamental "disconnect" between producers of consumer products and waste management, raises special difficulties.

Consumer product companies have done their best to be environmentally responsible, studying packaging reduction, sales of concentrated products, etc. They have included recycled content in packages. However, few significant steps have been taken to increase the recyclability of the products; elimination of base cups in PET (polyethylene terephthalate) bottles is a notable exception. This paper explores the gap between product design and recyclability. It brings the missing component to packaging design: the technology of materials recovery. The objective was to develop overriding design concepts.

INTRODUCTION

Within the last several decades, the growth in disposable products has been the greatest political impetus behind solid waste regulation. Public concern about disposable materials outlived the "landfill crisis" of recent years. The public reacts to visible litter. Thus, disposable materials, particularly packaging, are often specific targets of recycling-related legislation, such as bottle bills and advanced disposal fees. Recycling costs are dropping, but net savings often remain elusive [Powers, 1995]. Collection technologies, such as they are, present difficulties in broadening recycling. Markets, while

currently good, are notoriously unstable. Peaks in recycling rates, according to a recent Franklin Institute report, are far lower than goals set by many state legislatures. Trends are flattening [Rabasco, 1994].

TABLE I PLASTIC CONTENT OF VARIOUS SUBSETS
OF WASTE
(NUMBERS DO NOT SUM DUE TO ROUND-OFF)

PLASTIC	PERCENT OF STREAM CONSTITUTING PLASTICS		
	Plastic	Packaging	Total Waste
PET	7.0	.79	.26
PS	11	1.2	.41
HDPE	31	3.5	1.1
LDPE	31	3.5	1.1
PVC	5.6	.63	.21
PP	10	1.3	.37
Misc.	4.4	.50	.16
Total	100	11	3.7

Industries may argue that their product constitutes a small

contribution to the waste stream; the waste stream, however, is made up primarily of small components. The solid waste problem results from the size of the total. It is legitimate for waste managers to focus on the many "small" contributors to the waste stream. Table I [Franklin Assoc. 1988, Resin Report 1989] analyzes plastics in this light. Packaging wastes, as a whole, make up 33% of all waste; plastics are 11.2% of packaging wastes; the largest plastics components are 3.5% of all packaging. Plastics make up 3.7% of all waste by mass (these data vary considerably with source); the largest single component of plastic wastes are 1.1% of the total waste. The smallest specified component is 0.21%. Assuming a typical urban facility's receipt of 2000 tonnes per day, that still results in the arrival of 4.2 tonnes of PVC (poly-vinyl chloride) per day. The old adage obtains: a small percentage of a huge number is still a big number. Any waste reduction must assess the value of diverting all components of the stream, the vast majority of which will only constitute a small fraction when refined to raw-material-quality specifications. The most salable recycled product results from the tightest definition: pure PET has a far higher value than mixed plastics. This means that the best separation technology will yield the highest-value product; by extension, the recycling industry must then produce the greatest possible number of closely-specified products.

In the broader context of recycling, collection costs become the major issue in determining feasibility. The writer has calculated a 40% increase in collection costs [Stessel 1992]. One of the few broad surveys shows a cost increase of 60% comparing standard recycling to a landfill-based disposal system [Powers 1995]; that this is the highest ratio of all the options explored is not discussed. Materials with low bulk-densities are very hard to collect without compaction, and compaction causes its own difficulties in the collection of materials that must be processed for recovery [Stessel and Pelz 1994]. The major examples in this paper, aseptic containers and rigid plastic bottles, are alike in this difficulty. Problems incorporating aseptic containers and plastic bottles in recycling collection systems due to collection and processing costs are legion, and have gone as far as causing attempted bans [O'Conner, 1993; Scarlett 1993; Lieb 1994, Steuteville, 1994].

Thus, to meet recycling goals, assuming they are not rescinded, more materials will have to be accepted, from an expanded and simplified collection system, and materials recovery technology will have to be able to segregate components. This paper begins by describing the recycling system, in the context of the materials recovery facility (MRF) being the "gatekeeper" to an automated raw-materials-from-waste industry. The paper finishes by explaining that disposable materials must be designed with an eye towards "disassembleability," such as is now happening with automobiles. Thus, the paper concludes, it is not possible to design a disposable product without understanding the technology of materials recovery.

RELEVANT ASPECTS OF THE RECYCLING INFRASTRUCTURE

There are two fundamental problems with recycling systems

embodied in the discussion in the section above: (1) even with rising prices for recovered materials, it is not clear that recycling is a profitable operation when collection and processing costs are taken into account; (2) diversion of materials from recycling seems to be reaching a plateau. These phenomena are related.

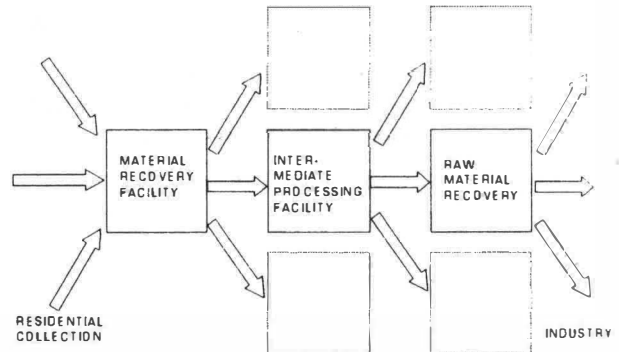


FIG. 1 ORGANIZATION OF RECYCLING AS A RAW MATERIALS INDUSTRY

The management of waste materials is an important component of a discipline called *resource economics*. Waste disposal returns materials to the environment. Disposed-of materials have at least as low a value as the original natural resources; in reality, they often have zero or negative value. The big financial question is the cost of recovering raw materials for industry from waste, as opposed to recovering them from the natural environment. Enormous strides have been made in packaging technology, but attendant perceived costs of disposal constitute market externalities. The current economic system fails to connect the economics of local waste taxation with disposable material production in any meaningful way. Yet, however idealistic one might wish to be, recycling cannot continue if it does not evolve into a cost-effective practice. Cost-effectiveness requires an industrial approach, transforming recycling into a legitimate raw-materials industry. Such a structure is shown in Figure 1.

The real difficulty lies in the missing link: recycling technology. Costs of automated processing using commercially available systems are almost always considerably lower than hand processing [Stessel and Murphy 1992]. Cost-effectiveness in the recycling industry requires simultaneous development of separation and re-refinement technologies, beginning with collection technology, before recovered materials can take an effective place in the raw materials market. One can increase the technical and economic success of waste processing by either improving separation technology or changing the characteristics of the processed material to enhance the abilities of existing technology to separate it.

MATERIALS RECOVERY TECHNOLOGY

All processing, however, begins with the MRF. If the material is to be recovered for further processing, it cannot enter the MRF reject stream. Increased attention to

automation is required to meet the goals of broadened materials acceptance with increased recovery. The MRFs de facto function as gatekeeper to the materials recovery industry continues unabated as processing technology continues to improve.

There are several proprietary systems on the market. Most of their uniqueness centers on the desire to segregate bottles. CRINC's chain curtain and the Brini vibrating incline screen are examples. This section of the paper focuses on traditional unit operations performing separate functions in segregation. The concept arises from the days when resource recovery implied front-end processing. Such process-train systems, or separation units based on those devices, continue to be marketed primarily by companies that continue in the market from those days. Even in analyzing newer, multi-purpose units, the discussion of the capabilities of individual unit operations yields insights. Indeed, the wider the range of incoming materials, the more likely that process trains will be required.

There are three broad categories of operation: (1) Mechanical disassembly separates components physically. Separations that are meaningful to recycling depend upon the initial design of the disposable item. (2) Separation by particle properties depends on such features as size, shape, and mass. This is both a function of previous unit operations, and the initial manufacture of the product. (3) Separation by material property, such as magnetism or color, is less dependent upon manufacturing decisions. Below, unit operations are listed. It is assumed that the reader is familiar with them; the purpose here is to list them in the context of MRFs, on which to base the next section of this discussion.

- Flail mills are one of the size reduction devices most suited to MRF operation. In some cases, they are employed as bag-breakers, with a desire to release, rather than size-reduce, the bag contents. Specialized bag-opening devices remain in their infancy. Flail mills' mode of operation comprises impact without restricted outlet. The violence of the operation is thus suited to separating loose mechanical bonds, such as a lid from a plastic cocoa container. The primary difficulty with their use as a primary step in MRF operation is glass breakage. This writer has previously recommended that recyclable materials segregation in collection be done automatically, with an air knife, primarily to differentiate between those lighter streams that are suitable to compaction, and denser streams, including glass and bundled newspapers, that either would not benefit from, or would be harmed by compaction [Stessel, 1992]. With such a collection system, the stream from the vehicle's compactor could enter the flail mill. Bags would be unnecessary because recyclables would be completely contained and covered in their own section of the waste container. In fact, bags would be undesirable because they would have to be opened before the air knife could do its job.
- Three types of screens are often employed: trommels, finger screens, and vibratory flat-bed screens. Older resource recovery facilities specified trommels of sufficient diameter that cataracting glass bottles would break upon hitting the

bottom of the screen. The objective of breakage has largely been discredited. One may still seek agitation in any screening operation to force apart items that have become stuck together, such as with dried food residue.

- Many items can be separated with flotation. When the objective of resource recovery was primarily the production of refuse-derived fuel (RDF), moisture in the product was a disadvantage due to the significant energy demand for drying prior to ignition. If automation is employed to increase the types of materials collected by relaxing the specificity of citizen instructions, one must be willing to accept a larger reject stream, at least initially. Studies have indicated that extraction of recyclables will almost certainly not lower, and may increase, the heat content of the stream [Murphy, 1989], so the use of water elutriation may still not be universally applicable. As discussed above, however, evolution of recycling into an industry may well involve sequential processing, requiring shipment of materials to facilities performing further cleaning. Issues of putrefaction and odor arising from organic residues then become a problem, making an initial washing step aesthetically desirable. However, without thorough drying, one may then have to ship significant quantities of water. Subsequent separation steps may make it desirable to ship whole containers, from which emptying water is notoriously difficult. Waste-water becomes a major operating concern for the MRF.
- Air elutriation, employing air knives or air classifiers, can often accomplish similar separation tasks. Even with plastics, an early evaluation of the potential for air separation gave results that indicated that further research was warranted [Stessel and Pelz, 1994]. Problems with water in shipping, combustion, and MRF operation would be avoided. Odors may remain a problem, although air classifiers provide substantial drying that may mitigate putrefaction sufficiently for bulk shipment. Even air classifiers are relatively simple unit operations, although they have been little employed in MRFs. Judicious application could result in separation of film plastics from rigid containers, as an example. Aerodynamic behavior depends significantly on the configuration of the object. With wide application of air classification in MRFs, it may be possible to separate an aerodynamically-heavy packaging component (thick cardboard backing, for example) from a light component (a blown-plastic bubble, for example) after the two have been separated with prior agitation (the flail mill or trommel, for example).
- Magnetic separation is so widely accepted as to require little discussion. However, its ease-of-implementation may confer benefits to other types of packaging that do not currently use steel. For example, all PVC containers could be manufactured with a steel collar, perhaps forming part of the tamper-proofing system. By distinction with the examples discussed above, the steel ring would be designed to remain on the bottle, not only after the consumer has opened and used the contents, but also through MRF agitation. The PVC container would then show up with the steel products,

from whence it could be separated with an air knife. The steel ring would be removed by the facility accepting PVC containers for further processing into industrial feedstock.

- Eddy-current separators are enjoying a resurgence. The popularity of aluminum beverage cans makes recovery equipment worthy of attention, despite a price that typically exceeds those of other unit operations designed for similar feedrates. An example of potentially-lucrative sequential processing may be found in non-ferrous metals. With broad instructions to the citizenry, asking that all metals be placed in the bin for recycling, the recyclable-materials stream will include cast and forged aluminum, as well as other metals. Some, like copper, may prove quite valuable. It is unlikely that distinctions among non-ferrous metals is appropriate for the MRF. The MRF may, however, employ an eddy-current separator simply to generate a stream of mixed non-ferrous metals. These would be shipped to another facility that would have multiple eddy-current separators, adjusted differently, interspersed with air classifiers and screens, to further segregate the non-ferrous metals by metal and manufacturing process (beverage-container recyclers do not like forged aluminum, for example). The required relatively high investment and advanced metallurgical knowledge would be appropriate for a centralized facility.

While the list above has focused on equipment that might be expected at a highly-automated MRF, one cannot ignore subsequent processing in designing the product for recyclability. It is vital that the majority of an individual material find its way into the correct stream at the MRF, preferably not the reject stream. In many cases, the MRF will produce mixed streams. The last example above, of mixed non-ferrous metals, is valid, although not of great current relevance. More relevant is separation of plastic polymers. With co-mingled plastics, it is desirable to continue to separate based on whole-piece characteristics as long as possible. An advanced separation facility can use x-ray, ultraviolet, and infrared detectors in a detect-and-route system to direct different objects to different streams. If, however, at the stage of the detect-and-route system, objects remain multi-material, the job of the detect-and-route system becomes much more difficult, and the resultant separation declines in value. Thus, the initial guidelines for product design that enhance MRF performance are valuable in later steps. Continuing with the example of plastics, final recovered-material processing might involved such advanced techniques as solvent extraction. The nature of reject streams, and the regulatory and economic limitations of process-chemical use, from such a process make it clear that the maximum of advanced physical separation is desirable.

PACKAGING DESIGN

Packaging is an extreme example of disposable waste. Both the aseptic container and plastic bottles are examples of packaging that has received significant attention due to recycling problems. For the consumer, the value is principally that of allowing a convenient method of conveying the material to the cupboard. To the manufacturer, distributor, and retailer, it has the benefits of: providing units of sale, protecting the contents

from spoilage or damage, and advertising. While the consumer expects products in good condition, the function of packaging is transparent; the sporadic outbursts against excess packaging and popularity of bulk-goods sales indicate that the consumer may doubt the value of much packaging as currently employed.

Once the consumer has emptied the package, its value turns negative. The consumer must pay for disposal.

For the commercial sector, packaging must protect product at reasonable cost. Protection involves impact protection, oxygen exclusion, pathogen exclusion, and/or radiation exclusion (usually ultraviolet and visible light). Cost-effectiveness involves low manufacturing cost, and reduction in shipping costs through low weight and efficient shape. Marketing issues include good package use of display space and the ability to draw the eye. All these are topics of entire programs of study in packaging engineering, design, and economics at universities.

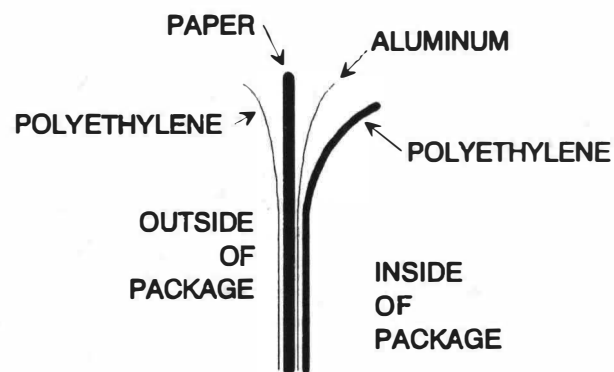


FIG. 2 LAYERS IN AN ASEPTIC CONTAINER

By incorporating a number of materials in layered fashion, the aseptic container is able to meet an extraordinary range of packaging requirements using an exceptionally material- and space-efficient package. Figure 2 shows the layers in an aseptic container. Starting from the inside, the polyethylene inner coating provides an inert liquid barrier. The aluminum acts to further restrict the passage of oxygen, and to prevent passage of light. The paper gives the package its rigidity. The outer layer of polyethylene prevents wetting of the paper from external moisture and provides a good printing surface. By mass, polyethylene constitutes 24%; paper, 70%; and aluminum, 6%. While products in other containers can be sterilized to permit long shelf-life, the aseptic container allows a reduction in the time of exposure of the contents to elevated temperatures, providing better flavor and nutrient retention for the contents. Using fruit juice as an example, aseptic packaging reduces the amount of material used to ship a given volume by 70% over traditional methods; this reduction also manifests itself in shipping cost savings. Further reducing shipping costs is the very efficient use of volume: using single-serving containers as an example, aseptic packaging allows shipment of 14 times the amount of consumable material in an equivalent volume compared to glass bottles. [APC 1992.] For milk, multi-layer containers may be used that are 80% paper and 20%

polyethylene [Miller 1993].

Thus, aseptic packaging contributes to the highest initial goal in waste control: source reduction. The Aseptic Packaging Council (APC) estimates their waste as 0.07% of total packaging [APC 1992]. The difficulty is that it is a quintessential disposable material: it is nearly impossible to re-use, and causes enormous recycling problems. The currently-recommended processing system involves use of hydro-pulping, which has the primary goal of recovering paper. The long paper fibers that are recovered are of good quality, leading to high sale prices of \$90/ton to \$150/ton for the containers where a market exists [Miller, 1993, Lieb 1994]. The design of the package makes it very slow to degrade in landfills [Miller 1993]. In composting operations, it provides a valuable bulking agent, but the non-degradable components cause unacceptable compost product appearance [Rodriguez *et al.* 1995].

Any alteration in package design must respect content protection requirements. In almost all cases, this is inviolate. Manufacturing and shipping costs can be allowed to rise, but only if the economic system permits full accounting of the costs offset by increases in manufacturing and shipping expenses. Marketing issues may be argued from the standpoint of relative advantage; a uniform mandate for product design for recyclability would retain a level playing field for all market participants. The latter issues are better discussed in public policy arenas.

DESIGN FOR RECYCLABILITY

Above are described (1) the recycling system into which disposable materials must go, (2) typical processing options in an advanced MRF, and (3) key attributes of aseptic packaging as an example. Two examples of design for recyclability will furnish lessons from which conclusions are drawn: plastic bottles in general, and aseptic packaging in particular.

Both types of container are used to contain putrescible materials. Despite instructions, people do not wash the insides of containers before placing them for recycling. The odors, prior to collection, can be remarkable [Miller 1993]. The only solution is the same as with the entire concept underlying waste management: collect before it becomes a nuisance or a health problem. The more one can recycle, the more frequently one can collect recyclable materials. For example, recycling a genuine 50% of household waste will result in pick-ups as frequent as those for solid waste. Designing products for recycling will make it more feasible to collect more material more cost-effectively.

Plastic Bottles

As has been alluded-to above, the plastic container industry has been very active on recycling issues. The plastics-container industry suffers by distinction with the aluminum beverage container by having a plethora of polymers. Recently, a group of manufacturers and cities cooperated on evaluating plastic container design [Anderson, Kelly, and Rattray, 1995]. Because of the seminal nature of this work, their list of recommendations will be paraphrased:

1. Caps should be compatible with the bottle. HDPE (high-

density polyethylene) bottles should use HDPE caps; other cap materials should be eliminated. Bottles whose color has been left natural should not employ pigmented caps. If other cap materials are employed, the entire closure should pull off when the container is open; the practical implication is that the security ring should remain attached to the cap, and not remain around the bottle's neck.

2. Label adhesives should be water-soluble for easy removal during washing steps. Metallized labels should be avoided where they will harm gravity-separation steps such as flotation devices. Chlorine-containing plastics should be avoided for labels on all but PVC bottles. Print should not be directly applied to containers, with the exception of date coding.
3. Industry participants abstained from discussion of a recommendation that PVC containers be avoided for products available in look-alike containers made from other materials. All agreed that more research was required on PVC detection and removal equipment.

Some discussion in the paper reporting this work elaborated on "MRF Vertical Integration," in the context of which it was recognized that one could not necessarily expect MRFs to produce a market-ready material with all the necessary cleaning steps for each material. The authors recognized this as particularly true of smaller geographic areas. The importance of the explicit recognition of the concepts in Figure 1 by industry and recyclers cannot be overstated. On the other hand, only three plastics were of interest: PET, HDPE, and PVC, the last as a contaminant. Even though an important linkage was formed by this work, much needs to be done before the scope of recyclable materials is encompassed. EPA finished their report of this work with the statement, "Once they finalize their recommendations, the next step is to reach industry trade associations, product manufacturers, packaging designers, recycling officials, and others." [U. S. EPA, 1995]. It must be noted that, while separability of incompatible components was the key issue in this report, technology for separation was not discussed.

Aseptic Packaging

Aseptic containers are a growing component of waste that have significant advantages in source reduction and product longevity, but which gain those advantages at the expense of recyclability. However, the components of aseptic packaging are, individually, readily marketable:

- Extruded aluminum has a ready market. Aluminum foil is being increasingly recycled separately from aluminum beverage cans, albeit at a modest price.
- The paper in aseptic packaging is of a very high quality: a premium is placed upon the use of a small amount; that small amount must furnish the container's shape and rigidity. Among old papers, aseptic packaging paper, if recovered with acceptable contamination, will fetch a high price.
- Two types of plastic are commonly recycled, where the barriers discussed above do not prevent their inclusion in recycling programs: PET and HDPE. Due to its presence in

garbage and grocery bags, film plastics are of considerable interest, although the separation difficulties that they bring are viewed as unacceptable in the U. S. Film recovery systems have existed for several years in Europe [Perrone 1988]. Most film in the aforementioned sources is low-density polyethylene. Thus, the film in aseptic packaging would fit in with a frontier in plastics recovery (film) and an accepted market (polyethylene).

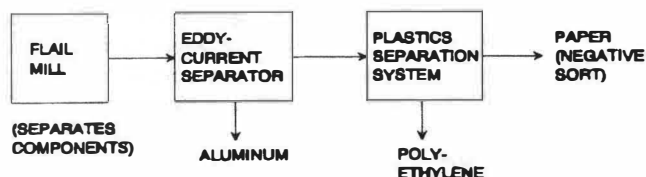


FIG. 3 MRF UNIT OPERATIONS SHOWN IN THEIR ROLES FOR ASEPTIC PACKAGING SEPARATION

Figure 3 shows a process train, made up of unit operations as discussed above, performing tasks according to their typical functions. The plastics separation system would be an air knife. However, the configuration of unit operations shown in Figure 3 ignores the bonding among the components of the aseptic package. It is exactly that bonding, as with other disposable materials, that renders MRF-level separation nearly impossible. The commercial food products industry offers an alternative concept. Milk is shipped in bags that are housed within corrugated cardboard boxes. The bags are not bonded to the boxes at all. A nipple extends through the box; for use, the box is inverted into the dispenser, the nipple is inserted through a mechanical pincer that acts as a valve, and the sealed end of the nipple is snipped off. A flail mill, as in Figure 3, would separate the two components of the commercial package easily in a MRF.

Similar to the commercial product, the aseptic package might be re-configured for separability. To allow each individual component of the package to remain intact through both the manufacturing process and the MRF, it is foreseen that individual layers would be thicker. Immediately, thickening the container would offset the tremendous weight advantage that aseptic packaging gives. However, with thicker individual layers, it might be possible to reduce the number of layers. Figure 4 shows a number of possibilities.

- (a) The original package layering could be retained, albeit without bonding. This could be taken as a control case, because it would be likely that layer thickening would be necessary for strength, and retaining the original product composition would fail to take advantage of possible simplifications due to less-permeable individual layers.
- (b) In line with commercial food packaging, the outer paper layer could be strengthened, and the inner plastic layer thickened. The combination might provide resistance to light penetration; the thicker plastic might provide adequate oxygen exclusion.

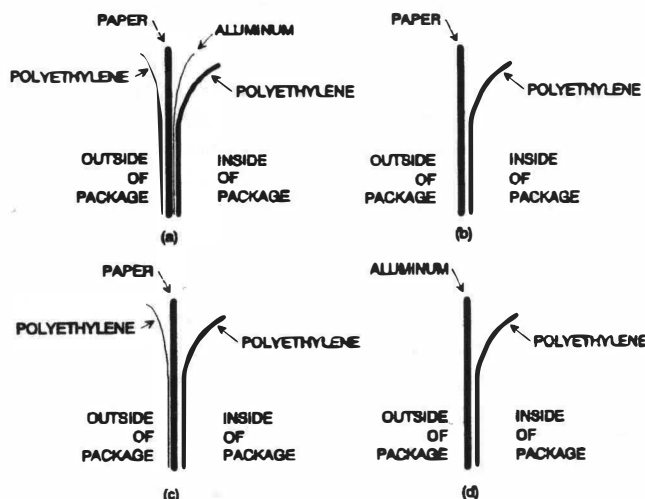


FIG. 4 VARIOUS POSSIBLE CONFIGURATIONS FOR NON-BONDED LAYERED ASEPTIC CONTAINERS: (A) ORIGINAL LAYERS; (B) CARDBOARD AND POLYETHYLENE; (C) MILK BOX; (D) ALUMINUM BOX

Alternatively, the inner plastic layer could be replaced by high-density polyethylene (HDPE), which, due to its greater rigidity, would result in a minimal need for cardboard. However, elimination of cracking would require rounded corners which would reduce space efficiency.

- (c) This configuration is exactly that of the milk box. The outer plastic coating would reduce the need for a tough cardboard exterior. The variations for the interior bladder would remain those of (b). The coated paper exterior would be far less recyclable, although with coating on only one side, pulping could remove the paper, leaving a polyethylene film.
- (d) An aluminum box could be formed to house an inner bladder. The bladder would provide the liquid containment. As the aluminum would be destined for recycling, its net cost would be small.

The closure system would be the objective of further design. It would be ideal to have a closure system whose multiple components would be separated by the very act of opening the container, as with removing a lid from a bottle.

While the plastics bottle industry has begun to consider three polymers, as discussed above, out of at least six that need discussion, the aseptic packaging industry relies on hopes that MRFs will incorporate hydro-pulpers. The disadvantage of water-based unit operations at MRFs have been discussed above. Plastic film is also not considered by the plastic bottle industry, but it is widespread in waste and recyclable; its basic

component is the ethylene mer. Thus, all components of the aseptic package should be considered very recyclable.

RECOMMENDATIONS AND CONCLUSIONS

Recommendations are divided into three areas. The first, and major group is recommendations for disposable material re-design. The necessary research infrastructure to produce successful designs is briefly discussed next, with a reference. Finally, necessary economic analyses are briefly described.

Design for Recyclability

Product design must be undertaken with a knowledge of MRF configuration. Beyond the MRF, the materials recovery industry suggested in Figure 1 would become material-specific. As the recovered material moves through different facilities to become an industrial feedstock, the industry consuming the final product (feedstock) would have an increasing role in determining the process configuration. At the MRF level, however, all industries are at the mercy of that which has become adopted by local governments or those contracting with them to accept the materials from recycling routes.

The Process Trains Concerning the steps in the materials recovery industry that affect product configuration:

- (1) The final, desired industrial raw material that will result from the recovery industry must be fully specified. Regardless of the final disposable product configuration, all current materials and their likely substitutes should be examined in this light. A true raw-material approach should be taken, not just a use for "recovered materials": for example, if HDPE is a current component, then the initial analysis should assume the re-processing of HDPE to virgin quality.
- (2) Current industrial, not recycling-market-based, needs should be considered next in examining a slight retreat from virgin material. For example, if pigmented HDPE is employed in the product, as currently constituted, the breadth of applicability for the exact pigmentation employed, in the context of all other possible pigmentations, must be examined. For example, if two methods of coloration are incompatible, it will be necessary to make certain that the recovered-material industry can be provided equipment to separate them.
- (3) The overall markets, including competitors and completely unrelated industries, for the material under consideration must be evaluated. If the material under consideration is not used in sufficient quantity in the manufacture of disposable products, there may not exist, or may not evolve, a component of the recovery industry for that configuration of material.
- (4) Taking (1) through (3) into consideration, it is next necessary to actually configure the industry. Working backwards, the first step would be to assign one team to establish specifications, and select equipment to meet those specifications, for the chosen industrial

feedstock/final recovered product. Often, final refinement stages in the existing virgin material industry will provide needed information. Solvent separation of polymers is a good example of an existing technology applied to this advanced stage.

- (5) Next, continuing to work backwards, intermediate processing must be considered. As an initial objective, the intermediate processing must take a commingled stream of similar materials and produce a single product suitable for (4) above. For example, mixed rigid plastics might be a starting point. Multiple plastics that might be found in rigid plastics must all be considered to determine separation technology that will result in an adequately pure stream of the polymer sought. This intermediate processing need not occur in a single facility. For example, non-ferrous metals might be segregated into element-based streams at one facility; a stream of stainless-steel might be sent to join the output of a ferrous-materials separation facility, while aluminum would go on to further intermediate processing to separate alloyed, cast, extruded, etc. categories.
- (6) Finally, the ability of MRF technology to produce a stream for intermediate processing must be considered. At this step, it may become obvious that intermediate processing will begin with facilities serving a wide number of raw-materials industries.

The Product With full specification of (1) through (6) for each potential material, the disposable product itself must be examined.

- (7) Each component must be examined for final recovered-material marketability. Is the component one of a class of materials that are commonly re-processed into valuable raw-material substitutes? If not, are substitutes possible that are more likely to join other streams in recycling, thereby enhancing the recovery value of the disposable product under consideration?
- (8) The product must then be examined for potential simplification. The simplification sought is in terms of numbers of materials employed, not physical configuration or manufacturing. A product including two materials will be less trouble to recycle than one including four.
- (9) The final form of each component of the disposable product must be examined for aspects that harm recyclability. A unique coloring process that cannot be reasonably undone will render an otherwise-valuable material worthless in recycling.
- (10) Finally, and most importantly, the product must be analyzed for ease of disassembly. Unlike initial assembly, the manufacturer must consider outside processes: the MRF and initial intermediate processing. Thus, packaging designers must become familiar with MRF technology. Specifically:
 - Minimize all forms of bonding unless it can be

assured that the bond will be undone in intermediate processing. Assuming, as above, that MRFs do not adopt water-based processes; water-soluble adhesives can be employed if intermediate processing will employ water, and both bonded materials will continue along recovery paths from the intermediate process. If one of the bonded materials will become a waste stream, while it would be recovered were it to join another stream at the MRF, then bonding should be avoided to ensure maximum recyclability.

- In conjunction with the above, MRF technology must be able to separate components. Most commonly, the product would have to come apart when hit with a flail-mill arm. A short bout of testing would affirm this behavior (see Research Needs, below).
- Adequate component size must be retained, in conjunction with conventions in materials use. This is in sharp distinction with "packaging minimization": one need not trouble to minimize packaging if it is economically recycled. If an adequate size is not retained, then the abilities of separation equipment to adequately isolate the individual object will be harmed. An historic example is the old pull-tab closures of earlier aluminum beverage cans. If non-ferrous metal recovery is to be employed, then all aluminum should report to that fraction, if the eddy-current separator is sized for aluminum cans. If a particular material is most frequently used for large containers, for example, HDPE for liter-and-larger bottles, then making a tiny HDPE bottle will harm HDPE recovery if a screening step is employed at the MRF to separate large containers from individual-serving sizes. Given the item directly above, size of a package component must be retained after the flail-mill step.
- Package closures must be designed so as not to harm the above. Rather than separate bonding agents, thermoplastics could be heat-sealed. Mechanical bonding, such as clips, could be employed; steel clips could easily be recovered in a MRF. Deliberately-weakened sections of parent material, such as thinned or partially-perforated sections could be used; the latter is employed on some aseptic containers. In some cases, the consumer could effect the separation: instead of the current gluing or stapling (staples are a contaminant), a plastic bubble containing a product on a display card could have a lip going all the way around the card, rather than on three sides; to open the package, the consumer would pull the cardboard away from the plastic, and no further separation would be necessary or desired.

All ten of the above are iterative. A recycling industry as

envisaged in this paper does not yet exist. Research and development will alter possibilities.

Research Needs

Obviously, MRF technology has yet to mature. It is difficult, however, to continue to develop the MRF with unstable and poorly-defined material destinations and markets. Currently, leadership in waste processing research is notable by its absence. The reason is that lines of responsibility are not clear: many solid waste initiatives originate at the Federal level; primary responsibility lies at the local level; the consumer-products industry is focused only on those materials they employ and cannot be expected to take responsibility for unrelated industries, and the solid waste industry is responsible for meeting contractual requirements set by local government. A unique level of cooperation will be required. An earlier paper has explored these interactions, earlier promising starts, and the consequences of continued inaction in research [Stessel and Spindler, 1994]. The waste management industry, the consumer products industry, and the federal government must all resume cooperative research roles. MRF technology must advance. Product design must evolve based upon true life-cycle costing. Materials selection and composition must include consideration of re-processing.

Economic Aspects

Recycling cannot continue simply as a fad. If it is not economical, it cannot be sustained. It is not adequate, however, to simply analyze the economics of recycling a product that was never designed to be recycled; the exercise is inherently self-defeating. Thus, economic analysis must be part of, and then incorporate, disposable products actually designed for recyclability. Of course, life-cycle costing is involved. Alteration in manufacturing costs, increases in shipping weight or dead space, and processing costs must be offset against avoided disposal costs and material resale revenue.

Integrated waste management includes recycling. A well-managed system is cost-effective. Good economics includes life-cycle costing. Simply examining costs in an unchanged system will not revolutionize waste management. Engineering and materials science will permit innovation. Proper engineering includes economic analysis. Proper engineering examines the whole of a situation. Engineered waste management will examine complete product cycles. Engineering recycling to expand its scope while improving its economics requires development of the entire system, beginning with the products to be recycled.

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