COMPLEXITY IN SOLID WASTE PROCESSING

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ABSTRACT

Automated solid waste processing is a very complicated task: complicated equipment should be considered despite the fact that it can cause inordinate downtime if misapplied. Examples from laboratory research and development are compared with reports of field experience to produce guidelines for distinguishing between the types of equipment complexity that are and are not acceptable.

A renaissance is beginning for automated solid waste processing. As opposed to the original concepts of single plants performing the entire waste-segregation task, processing is being considered for many different phases of waste management. Increasingly, processing is being called upon as simplistic waste management systems fail to meet objectives set by ambitious legislators. This discussion begins by exploring the reasons for inadequate performance of selected earlier efforts; covers current tasks required of waste processing, and the modern implementation of waste processing unit operations; discusses laboratory-developed changes in unit operations; and presents resulting development and design principles.

DIFFICULTIES IN EARLY EFFORTS

Initial efforts to mechanically process solid waste began in the late 1960s when it was realized that the solid waste problem was part of growing national environmental concern. At that time, it was recognized that waste quantities were increasing, that the complexity of the waste stream was increasing, and that management practices might be inadequate to protect the environment.

Resource recovery, in the original use of the term, began at that time. Mechanical unit operations were installed to extract recyclable materials from the waste stream. The production of refuse-derived fuel, or RDF, was viewed as one of many possible product streams, if often the principal one. Separation equipment was borrowed from other fields and adapted to resource recovery with very little research or modification, notwithstanding the clear increase in the complexity of the separation due to the increased heterogeneity. Few pilot-scale or demonstration facilities were constructed on which the industry could gather information about behavior of unit operations and scale-up properties, let alone conducting laboratory research to develop new devices [1].

Politically, the solid waste crisis has re-emerged. On this go-round, however, there is much less confidence in a "technological fix." Individual states are passing solid waste legislation at a furious pace. Much of that legislation mandates waste reduction. Lacking alternatives, solid waste managers are pursuing source separation or curbside collection. Several problems have been addressed with modest success: participation rates, even in ideal neighborhoods, do not meet expectations; multi-family dwellings and economically disadvantaged areas are not considered; recovered materials fail to find markets; and the systems prove very expensive. The results of these difficulties are that solid waste managers are having difficulty meeting their states' waste minimization requirements.

In efforts to solve these problems, material recovery facilities, or MRFs, have been added to curbside collection systems. The majority of these facilities use hand-sorting, employing persons of limited career outlook to remove easily-identifiable components from the waste stream (pickers). Such a facility is very labor intensive. Training costs are incessant, as turnover is high. Recovering, for example, HDPE by instructing pickers to look for 2 L soda bottles will leave a lot of HDPE in the waste stream; a thorough waste characterization will yield complaints that HDPE removal is inadequate, and overall waste reduction will be minimal.

Despite these difficulties, mechanical processing continues to be considered a poor choice for waste management systems. The history of mechanical processing has led to a great deal of skepticism. A waste management official, although very interested in the potential of automated processing, might feel that it could not be recommended to his superiors given the history of the industry.

It is very important that failures be examined so that lessons could be learned. This paper considers learning general design principles from the study of selected difficulties experienced in the field and laboratory research.

THE ROLE OF UNIT OPERATIONS IN PLANT FAILURE

While there are many documented failures in automated waste processing, there are few good technical data concerning reasons for failure. Certainly, the unit operations, individually and in combination, did not meet expectations for efficiency and/or reliability. Although there has been considerable effort devoted to defining solid waste processing efficiency in a meaningful fashion, there are inadequate performance data for individual unit operations in failed plants to allow comparisons to be drawn (for a discussion on standardization of efficiency parameters, see Ref. [2]). Further, studies of failure have not adequately isolated mechanical causes. Failing hard data, discussion must be anecdotal, selecting cases with difficulties in common.

In some cases, development of a large-scale system with inadequately-researched components leads to a need to improve performance in a manner that vindicates the original equipment selection, i.e., minor, inexpensive upgrades. In the case of the San Diego Flash Pyrolysis preprocessing train, significant use was made of baffles to increase residence time. Assuming that the original choice of equipment types was correct, the obvious fundamental problem was undersizing. The plant eventually closed, but it is not possible to determine if better preprocessing would have sufficiently enhanced revenues [3]. Reports from Recovery 1 commented upon the "steep learning curve" that they had not expected. They had considerable difficulty with magnetic recovery. Jams occurred between the magnetic separator and the conveyor. Paddles on the drum were found primarily responsible. However, increasing the clearance resulted in reduced recovery [4].

The processing tasks of individual unit operations are often sufficiently difficult without making the unit operations interdependent. The Americology plant in Milwaukee used the same airstream for both the air classifier and the secondary shredder. The resulting instability in the air classifier caused poor performance [5]. Recovery 1 used a single cyclone separator to process both the ferrous concentrator light fraction and the light fraction from the air classifier. Considerable difficulty in regulating air classifier airflows was found [4]. The extent of the penalty these practices would exact is obtained by reference to Hiers, Libey, and Wisely's discussion of the need for careful constant adjustment of the airflow [6]. Recovery 1's ferrous concentrator tried to distinguish between three product streams rather than concentrating on cleaning the ferrous product. This was corrected by replacing the concentrator with an air knife [4].

Many improvements to successful plants consist of adding unit operations. Once the basic plant is somewhat successful, the revenue stream can be enhanced by increasing product quality. The Ames, Columbus, and Milwaukee plants all added disc screens to reduce downstream problems. Milwaukee added a magnetic separator [5, 7, 8]. Similarly, the St. Louis–Union Electric Prototype had problems using pneumatic feeders with wastes from which only ferrous materials had been removed. An air classifier was added to further reduce components that would not likely be amenable to air conveyance and feeding. In none of these cases was the idea to recover another material. Rather, additional equipment allowed downstream unit operations to better perform their jobs.

Shredders are one of the most common, but most feared, unit operations in waste processing. In industries where they are recognized as essential, considerable care is spent on their design to minimize energy consumption and wear. Shredders are employed without comment in everything from ore processing to automobile recycling. As they were adopted in solid waste without proper research and testing, serious explosions resulted. Currently, there are enormous numbers of equipment and design options for fire and explosion suppression and containment [9, 10]. In addition, poor performance of subsequent downstream unit operations exacerbated the perception that one could not to justify the heavy capital and operating costs of shredding operations.

Air classifiers are one of the most studied unit operations in solid waste processing. Many designs evolved, virtually all of which involved complexity in the throat design. After a long-term study of such designs, Trezek, Savage, and Diaz concluded that "complexity is not necessarily a measure of . . . performance" [11]. In fact, while many of these designs performed better with low feedrates of ideal particles, operational difficulties increased. Hiers, Libey, and Wisely concluded from their experience in St. Louis that "close monitoring and frequent adjustment" were necessary to achieve even modest performance [6].

Lessons concerning system development are drawn below. First, it is necessary to re-state modern goals in waste processing.

REQUIREMENTS OF WASTE PROCESSING

To develop goals for waste processing, one may begin with the concept that the current difficulties with recovered materials markets are entirely a function of material quality. If it were possible to produce a recovered material with characteristics identical to virgin material, the market would be identical to the raw material market. Marketability of recovered material is entirely a function of the quality of those materials.

In order to meet standards for waste reduction, a waste processing system must not only maintain high purity standards that ensure markets and prices for the recovered materials, but must also recover sufficient quantities of the salable materials to reduce waste masses and volumes.

The waste management industry must begin to think of waste processing as they would any other industrial processing plant producing a raw material. The processing plant must meet or exceed standards for purity set by the market, treating the incoming solid waste as newly mined ore. Just as with producing aluminum from bauxite, the industry must research and develop the required unit operations to reach from the input to the output.

CONCEPTS IN COMPLEXITY

Extracting lessons concerning plant design from the above history of difficulties requires categorization of types of complexity. This begins with the understanding of objectives necessary to meet modern waste minimization goals. The preceding section discussed the objective of allowing the product to drive the processing stream. This section begins with implementation of that concept.

Present day implementations of resource recovery technology focus more on recovering individual, usable, salable products than processing the entire waste stream to recover broadly-defined categories. The modern approach often begins with a feed stream that is a subset of the whole waste stream, often derived from special collections. These plants begin with full awareness of the standards of purity that they must achieve to produce a feed for a given reuse application, and the recovery they must obtain for economical operation. With such a clear focus, it is possible to adopt complicated processing trains without objection, and to develop them successfully. The Center for Plastics Recycling Research's pilot plant employs 14 unit operations to recover HDPE from a feed consisting solely of bottles (see Fig. 1) [12]. The Italians are working on recovering plastic films [13]. One of their plants has the sole purpose of cleaning recovered film so that it may be reprocessed; this plant involves six steps as shown in Fig. 2. This is only one aspect of considerable effort for complete waste processing in Italy [14].

The overriding issue in waste processing is the complexity of the feed. There is no other industry that must handle a feed with such compositional complexity. Further, the feed is time-varying. Waste composition varies as vehicles arrive from different areas of town; waste composition often varies seasonally.

The complexity of time-variance is presented to the designer by the incoming stream. It is essential, therefore, to design equipment with the maximum of adjustability and flexibility. Adding adjustability at all points in the processing train acknowledges an existing problem, thereby reducing operation problems.

With a complicated waste stream, the tradeoff must be to replace persons capable of staffing individual stations along a hand-sort conveyor, with better educated and experienced persons who can learn to identify and anticipate variations in the incoming waste stream and make appropriate adjustments. Sophisti-

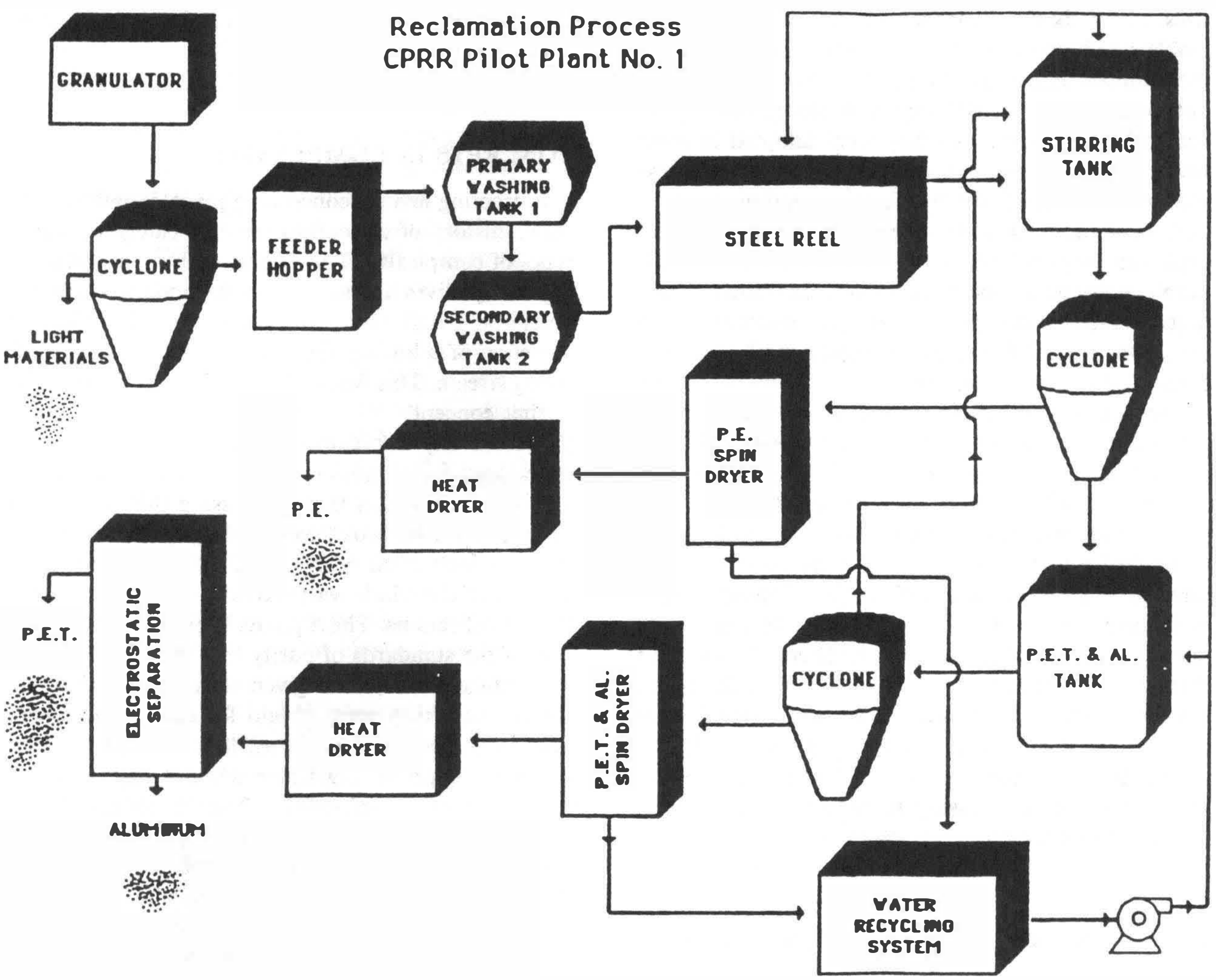

FIG. 1 FLOW DIAGRAM OF THE CENTER FOR PLASTICS RECYCLING RESEARCH PROCESS TRAIN TO RECOVER PLASTICS FROM CONTAINERS [12]

cated centralized monitoring, instrumentation, and control will reduce the numbers of these more-expensive personnel and allow them to react quickly.

For practical implementation, the systems approach extends to dividing the separation or benefaction tasks to their most elemental components. Waste is much too complicated to make any glib assumptions about multiple benefits from individual processes. The initial step is to consider individual unit operations for each elemental task, with each unit operation optimized for that task.

Complexity is thus reduced by increasing the number of unit operations while decreasing the complexity of the task assigned to each. The "food processor" approach to unit operations design will seldom achieve the theoretical optimum of a collection of separate steps. It is much easier to address specific problems during shakedown with distinct unit operations. In shakedown, modification, and ultimate performance, long-term economy will be demonstrated.

It is the task assigned to each unit operation that must be kept simple. As discussed above, success in the simplest of processing tasks may require sophisticated equipment. In developing individual unit operations, it is important to respect the nature of the feed. Jamming, clumping, and wrapping are common. These result from obstructed or tortuous pathways. It is often possible to implement individual operating principles with a number of design alternatives. It is essential to keep any protrusions into the waste path-

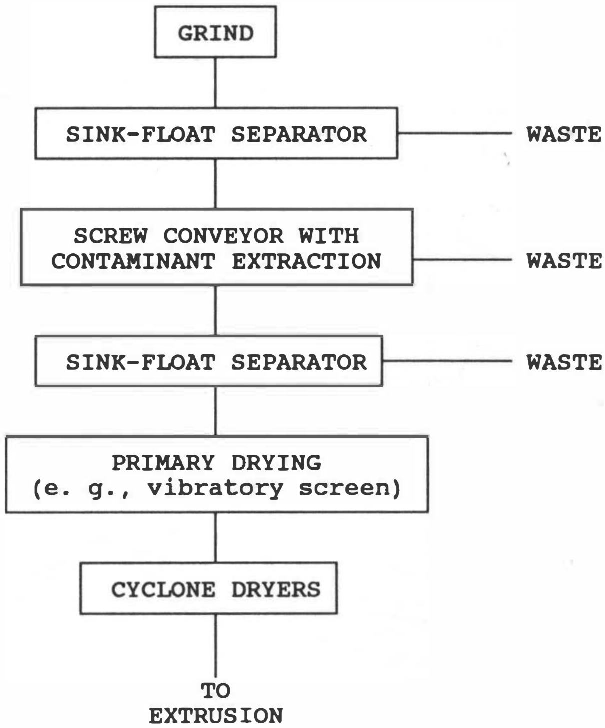

FIG. 2 FLOW DIAGRAM FOR THE FILM WASHING SEGMENT OF THE INTERNATIONAL PLASTICS ITALIANA LOW-DENSITY POLYETHYLENE RECOVERY OPERATION [13]

way to an absolute minimum, and to keep that pathway as straight as possible. Considerable complexity outside the waste/product paths is acceptable, because it can be designed for relatively known operating conditions. Anything in contact with solid waste must be designed to encounter anything.

Once individual sub-systems within the processing matrix have been addressed in design, the tendency to note similarities and attempt to reblend streams must be resisted. Repeated use of similar unit operations is acceptable because each must be specially modified and optimized for the individual task. In some cases (e.g., trommels at Dade County, Florida [15]) this concept extends to a sequence of the same type of unit operation, each sized to perform a different function. Particularly at this stage of the industry, given the complexity of the feed, it is not advisable to attempt to combine streams and unit operations.

This discussion has attempted to clarify and classify the complexity that must be faced in separation of solid waste, in a manner meaningful to the research, development, and selection of unit operations.

LABORATORY RESEARCH

Important lessons concerning factors governing the success or failure of unit operations can be learned in the laboratory. In the laboratory, development is preceded by research. Steps include:

(a) Define the problem to be addressed by the unit operation.

(b) From knowledge of the feed characteristics and processing goals, develop the fundamental operating principles of the unit operation.

(c) Develop designs that implement the fundamental principles in a manner that recognizes the difficulties presented by the feed.

(d) Construct an easily-modified, instrumented, laboratory-scale device.

(e) With low feedrates and/or ideal particles, test the device's implementation of operating principles.

(f) Test the device at realistic feedrates for its scale.

(g) Make modifications as indicated, and test again.

(h) Develop a pilot-scale prototype for larger-scale, continuous testing. Make modifications as indicated.

Several interesting progressions in equipment have been obtained in this manner.

Eddy current separators have progressed considerably. At the end of the heyday of resource recovery, the only commercially available machine was the Al-Mag. This used massive alternating current magnets; it was very expensive to buy and run. Raytheon developed a permanent-magnet system that seemed to work and was obviously much less expensive to run, shown as Fig. 3(a). Magnets of opposite polarity were mounted under a ramp down which the feed was directed. The writer developed concepts to enhance the Raytheon device involving placing magnets of opposite polarity on another plane above the ramp; further enhancement was to come from mounting both sets of magnets on belts and moving them independent of the speed with which feed passed down the ramp [unpublished]. In addition, airflow was added to reduce particle-to-particle interaction. Figure 3(b) shows this device. Recently, Dutch research began with the concept of the feed passing between two plates of magnets. However, to develop much higher fluxes, they had the brilliant idea to mount the magnets on parallel disks spinning on a horizontal axis and dropping the feed between the disks. This has the advantages that mechanical simplicity allows high rotational speeds, allowing significant fluxes to be developed; feed can then be dropped between the magnets and separated despite the speed of free fall. Free fall would also allow particles to move freely in accordance with applied magnetic fields with particle-to-particle interactions

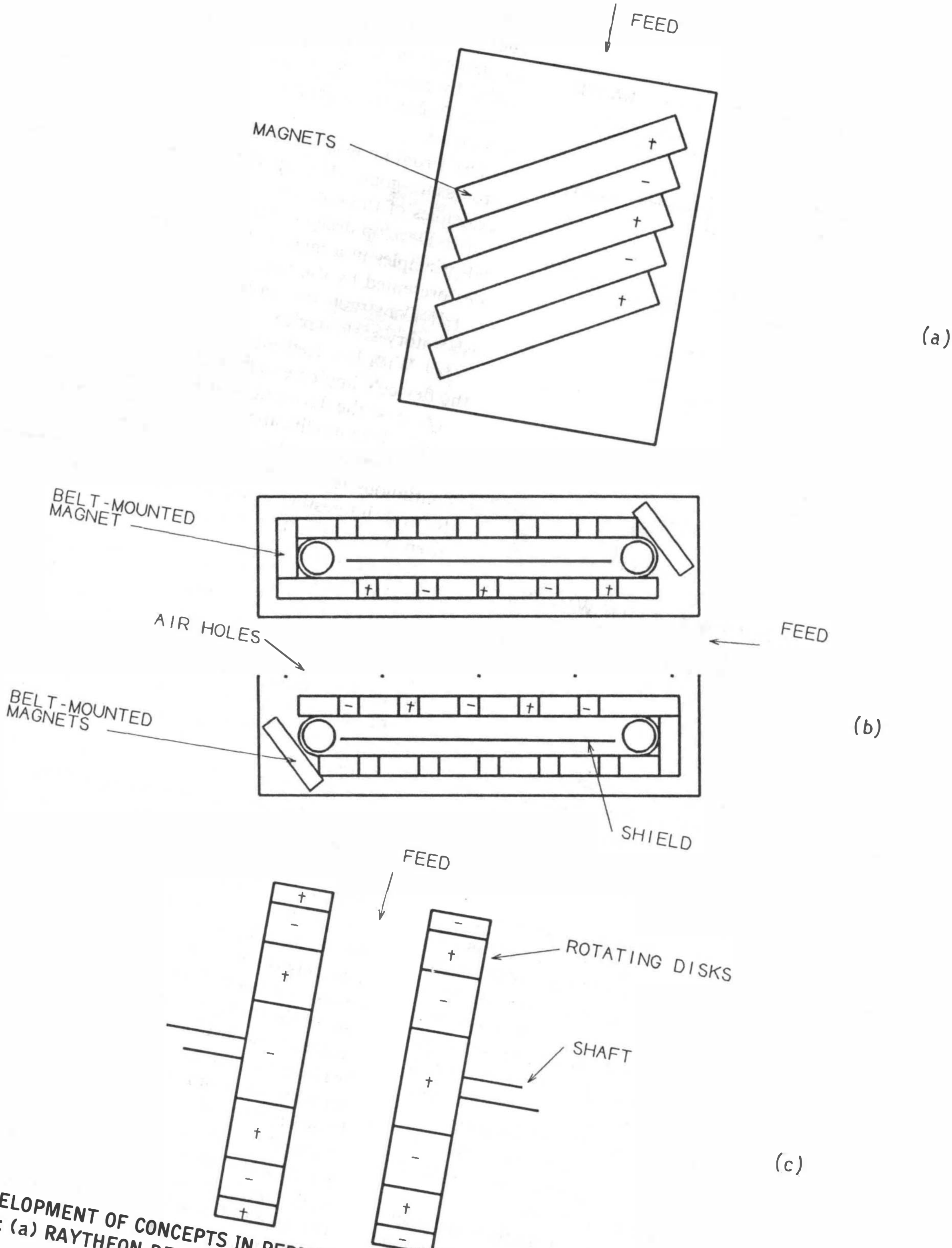

FIG. 3 DEVELOPMENT OF CONCEPTS IN PERMANENT-MAGNET EDDY-CURRENT NONFERROUS METAL SEPARATORS: (a) RAYTHEON DEVICE SHOWN FROM ABOVE; (b) CUTAWAY OF DOUBLE BELT-MOUNTED AIR TABLE DEVICE; (c) DELFT UNIVERSITY DEVICE [16]

minimized [16]. Considerable advantages in operation simplicity are thereby obtained. The device can be adjusted through an enormous range with little increased wear and jamming problems are considerably reduced by having particles in free-fall. Figure 3(c) shows a side-view of this device.

Air classifiers have had a considerable history in the solid waste processing industry. They have an even longer history in other industries, such as mineral processing and agriculture. Unfortunately, the separation tasks in solid waste processing are considerably more difficult than separating wheat from chaff. Traditional types of vertical air classifier include the straight rising and zigzag air classifiers. Performance has never reached expectation except when very simple requirements were set. Considerable effort has been devoted to modifying throats to enhance separation. Figure 4 (a) through (f) shows a chronological progression of such throat designs. The most common result was to enhance jamming. The active pulsed-flow air classifier, shown in Fig. 4(g), is based upon fluid mechanical theory that shows that pulsing airflow with an asymmetric pulse greatly enhances separation. The basic throat is simply that of a straight, vertical air classifier. The classifier operates under positive pressure. This requires a rotary airlock valve at the bottom of the throat, but eliminates the need for one under the cyclone separator; jamming and bridging are reduced, and the blower can operate more efficiently. The pulsing valve is entirely outside the feed stream. The pulsating flow has the additional advantage of breaking up clumps. It is very difficult to distinguish the extent to which the improved performance demonstrated in the laboratory occurs because of better density-based splits or breakup of clumps [17].

Feeding has always been a problem with air classification, where some type of airlock feed is needed; rotary airlock valves are often used, as shown in Fig. 5(a). Often there exists a chute between the valve and the air classifier throat that is necessary because of the vertical orientation of the throat and the configuration of the feed hopper/valve combination. Jamming frequently occurs beneath the rotary airlock. Following the concepts of increasing the level of equipment specialization, a miniconveyor feed system was developed. This allowed feed to drop vertically through the rotary airlock with no downstream constrictions. The feed would drop onto a very short conveyor that would move it into the throat. Figure 5(b) shows this combination. It was then determined that those devices could be recombined into the drum feeder, shown in Fig. 5(c). This is essentially a rotary airlock valve, except that the axle of the valve is itself a drum. There are many blades on the drum, allowing for good air sealing. The diameter of the drum allows a vertical feed hopper, and a perpendicular injection into the throat. Each chamber thus formed is more of a shallow box than the vee shape of the rotary airlock. The curved rear wall of the feed zone viewed from the classifier throat reduces disturbance of the airflow and enhances forcible introduction of particles into the airstream. Thus, a larger, much more cumbersome feeder presents better sealing, better injection, reduced jamming, and more freedom of layout than the traditional approach, and fewer moving parts than the intermediate research design.

Thus, by considering fundamental principles and the unavoidable complexity of the feed stream, interesting advances in design are obtained.

WASTE PROCESSING PRINCIPLES

The preceding discussion has developed concepts in development and design. By way of summary, these are listed in order of implementation below.

Waste Processing Development Principles:

(a) Develop in reverse, beginning with the product(s) to be sold.

(b) Determine the requirements for reliable sale of the product(s) at a good price. These include recovery and purity.

(c) Divide the processing into subsystems. For example, one subsystem may extract container-size objects. Another may separate container-size objects into plastic, glass, and metal. Another may separate plastic container-size objects by type. Another may break down container-size plastic objects of a given type into component plastic and other materials, cleaning valuable components and preparing them for sale. These systems may be in different locations and operated by different organizations or companies.

(d) Characterize inputs and outputs to each subsystem.

(e) Determine characteristics of the feed that will distinguish among the different products of the subsystem.

(f) Sequence the processes and separations required to use each product's characteristics to distinguish and separate it from the feed. These must be broken into their most basic steps.

(g) Determine the operating principles necessary to perform the processes and separations required.

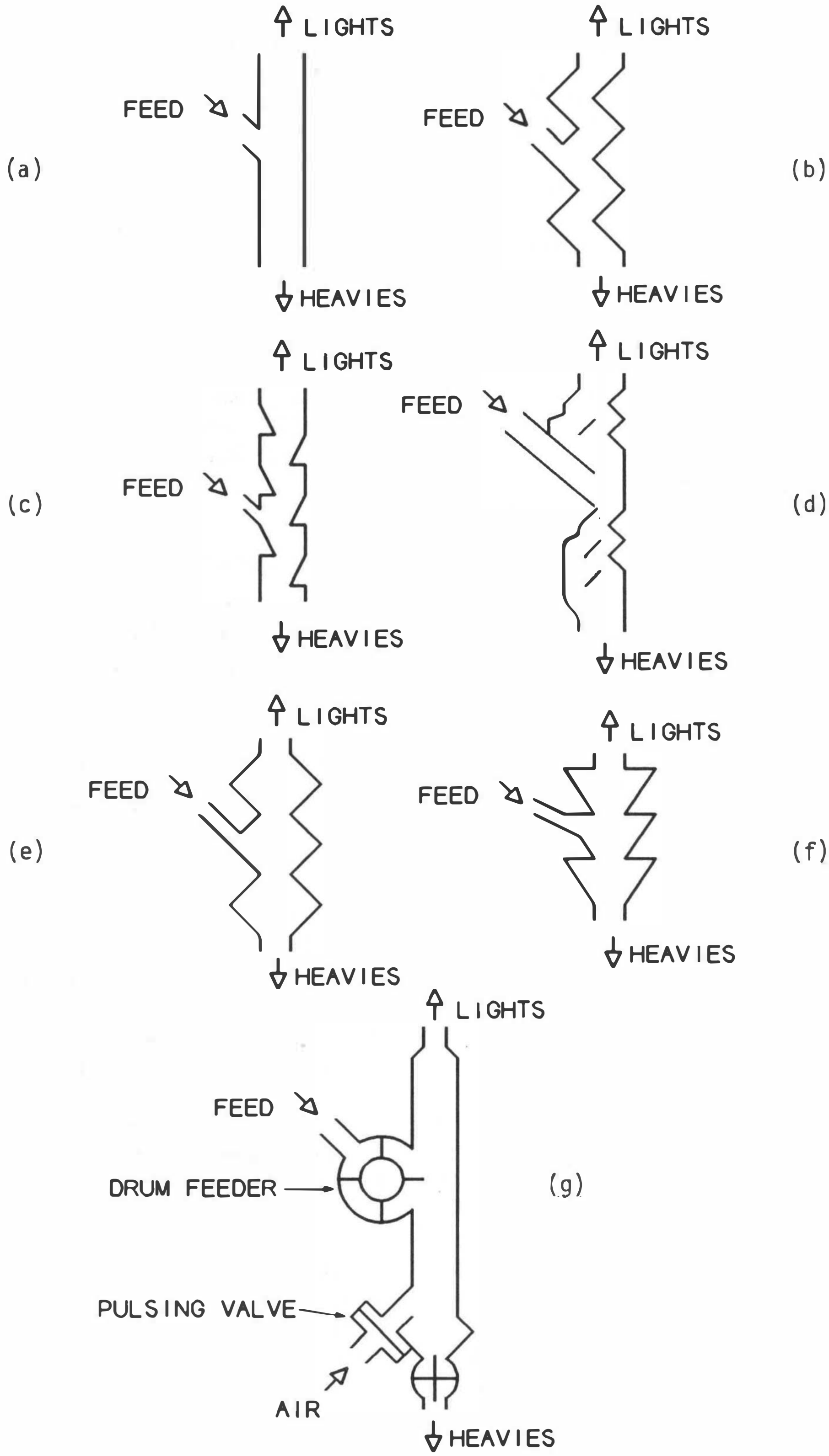

FIG. 4 CHRONOLOGICAL PROGRESSION OF VERTICAL AIR CLASSIFIERS: (a) STRAIGHT; (b) ZIG-ZAG; (c) UTAH THROAT; (d) DUKE THROAT; (e) ZAG-ZAG; (f) STACKED TRIANGLE; (g) ACTIVE PULSED-FLOW [17]

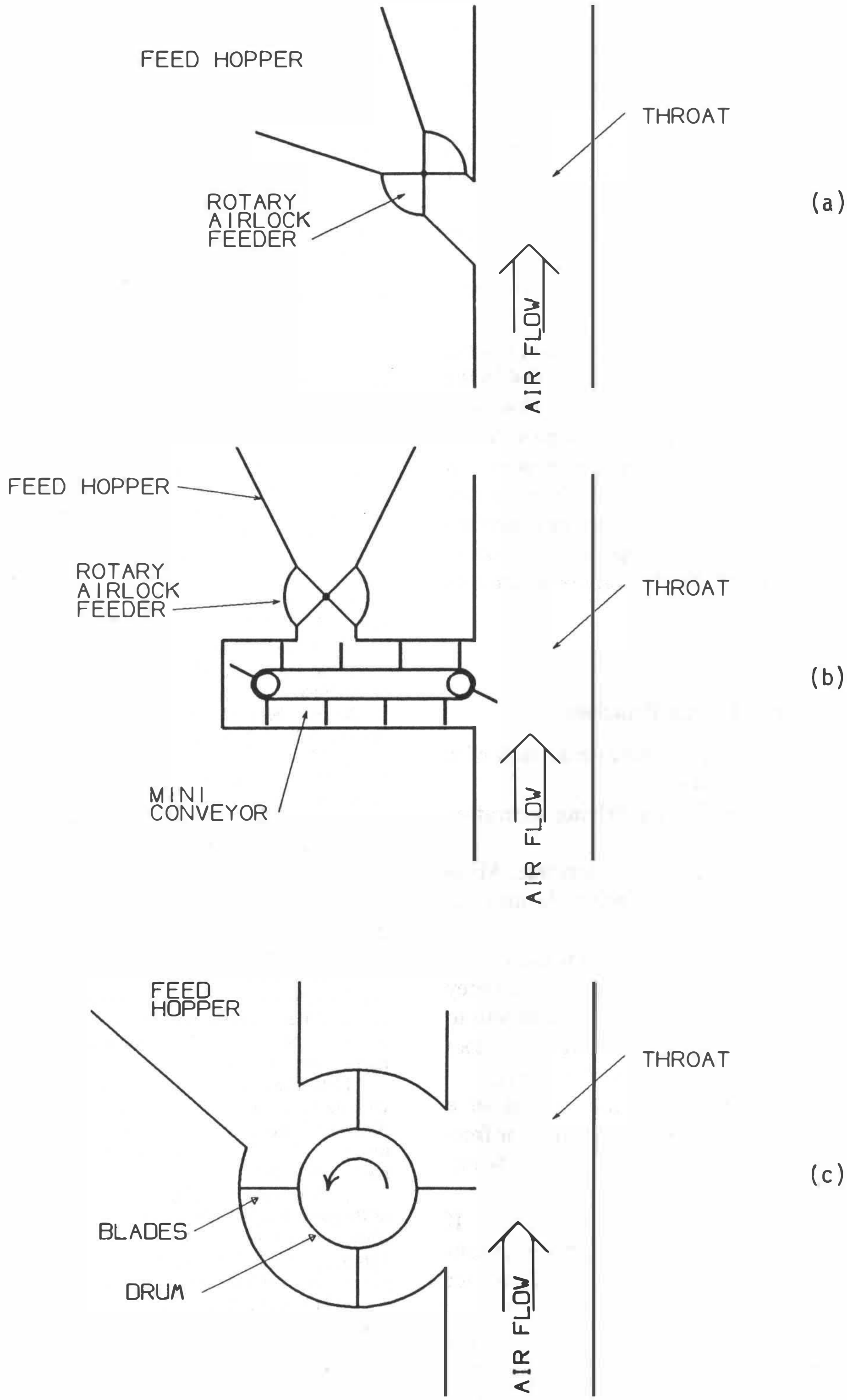

Fig. 5 DEVELOPMENT OF A FEEDER SYSTEM FOR AIR CLASSIFIERS: (a) ORIGINAL ROTARY AIRLOCK FEEDER; (b) ADDITION OF A MINI-CONVEYOR, ALLOWING OPTIMAL ORIENTATION OF THE ROTARY AIRLOCK AND ELIMINATION OF RAMP; (c) ROTARY DRUM FEEDER, OFFERING THE ADVANTAGES OF MINI-CONVEYOR SYSTEM WITH GREATER SIMPLICITY

(h) Perform a rough design on each unit operation in the chain.

(i) Determine if an exact such device is manufactured for each case.

(j) If a "roughly similar" device is manufactured, arrange to have the device tested and developed so that it exactly meets the processing need.

(k) If no such device exists, arrange to have research and development conducted.

(l) Conduct testing and development on the processing train for the entire subsystem.

Clearly, no one individual or company will perform these design and development steps to disassemble the entire waste stream into its component parts. However, as with any other industry, different companies should find market niches that will motivate the production of an intermediate product from solid waste or a raw material for another industry from an intermediate material. These development principles allow adherence to Walter's Fourth and Sixth Commandments of Resource Recovery [18].

Unit Operation General Design Principles

(a) Adopt a sequence of unit operations, each with easily-specified, simple objectives.

(b) Obtain or develop the underlying operating principles.

(c) Keep the material path obstruction-free. Minimize shafts, bars, baffles, etc. that protrude into the material path.

(d) Minimize tortuosity of the material path.

(e) Complicated devices are permitted, if: (a) they are necessary for operation of the device according to fundamental principles, and (b) the complexity does not result in protuberances into the waste stream.

(f) To move material into, through, or out of a device, maximize the use of forced-conveyance or free-fall. Principles 2–4 constrain selection of forced-conveyance alternatives.

(g) Minimize interdependency between devices. If common air or heat sources are required, make certain that fluctuations in one device will not adversely impact the other.

(h) Maximize adjustability. Employ valves, provide for adjustable slopes, select variable speed motors, etc. These must be implemented in a manner that will allow constant adjustment by operators or automatic control systems.

Taking the necessary time to properly research, develop, and test each individual unit operation for each application, as well as complete subsystems, will ensure that the difficulties of the past will not be repeated as the nation again strives to mine urban ore.

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