SEPARATION OF SILVERWARE FOR MACHINE VISION SORTING AND INSPECTION

By

SACHIKO HASHIMOTO

Bachelor of Education

Osaka Kyoiku University

Osaka, Japan

1991

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 1995

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Thesis Approved:

Thesis Adviser

Thomas C. Collins
Dean of the Graduate College

ACKNOWLEDGMENTS

I wish to express sincere appreciation to my major advisor, Dr. Lawrence L. Hoberock, for his encouragement, advice, and the many hours of guidance throughout by graduate program. My sincere appreciation extends to Dr. Ronald D. Delahoussaye and Dr. Eduardo A. Misawa for serving on my graduate committee. I wish to extend many thanks to Mr. Jerry Dale, MAE Research Lab Manager, for his guidance, support, and suggestions.

I would also like to give my special appreciation to my parents Hiroaki and Haruko Hashimoto for their support, strong encouragement at times of difficulty, love and understanding over the years.

Finally, I would like to thank the Oklahoma Center for Integrated Design and Manufacturing, together with its principal Sponsor the Oklahoma Center for the Advancement of Science and Technology, for financially supporting this work.

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NOMENCLATURE

A	peak to peak amplitude (in.)
CF	total vibrating centrifugal force (lb.)
CPM	frequency of vibration (cycle/min.)
ds	required static deflection (in.)
fd	excitation or driving frequency (Hz)
fn	natural frequency of the vibrating structure (Hz)
I	isolation percentage (%)
K	required spring rate (lb./in.)
LOAD	total "sprung load" of vibrating hopper, vibrator, and silverware load (lb.)
T	transmissibility
w	load per mount (lb.)

CHAPTER I

INTRODUCTION

Background on the Automation of Silverware Washing

Automation of commercial dish washing operations in large establishments such as hospitals, universities, hotels, and airline flight kitchens holds promise for reducing operating costs. Most such dishwashing operations employ unskilled labor for tedious and repetitious tasks in hot, humid, and dirty environments. Such jobs lead to absenteeism, poor productivity, and high labor turnover. Past and current research (Johnson, 1993; Russell, 1994) has addressed the automated washing of dish pieces, which includes high speed sorting and inspection operations. However, very little work has been reported for automated sorting, inspection, and handling of silverware. Because of geometric complexity, automation of such operations for silverware is more challenging than those for dish pieces. Even for those establishments that employ some automation in washing of silverware, substantial manual sorting and inspection operations are used (Ryan, 1994; Rowley, 1994; First Customer Service Group, 1994). This is due to two principal difficulties: (1) Metallic surfaces are highly specular, causing reflections that confuse vision systems; (2) Most silverware is washed in mixed batches, such that individual pieces overlap each other. Without separation of these pieces, most vision systems cannot deal effectively at required production rates with overlapping geometries.

As an example of a typical commercial silverware washing operation, we consider a private 700 bed hospital in the midwestern U.S. This hospital operates 3 two-hour dish washing shifts, each processing up to 700 trays of dishes (Johnson, 1993; Russell, 1994). Each tray typically contains four silverware pieces: a fork, knife, spoon, and soup spoon. These pieces are not sorted before washing because of space and time limitations imposed on pre-scrubbing and silverware loading operations at the upstream end of the process. Typically, all silverware pieces are mixed together in a batch container and passed through the dishwasher in the container. Thus, after the washing shift has been completed, one or two workers must sort and inspect up to 2800 pieces of silverware in less than two hours. Additional operations may require placing four different silverware pieces together, and rolling them in a napkin. Clearly the handling of silverware is a tedious and labor intensive process, making it a good candidate for cost-effective automation.

As an example of the application of machine vision inspection, Rigney and Kranzler (1994) are developing a system for measuring conifer seedling morphology. Well over one billion conifer seedlings are produced in the U.S. each year to support reforestation. Rigney and Kranzler have investigated automating the grading of seedlings, currently done manually, to improve viability after transplanting. The system automatically locates the seedling root collar and measures stem diameter, shoot height, sturdiness ratio, root mass length, projected shoot and root area, shoot-root area ratio, and percent fine roots. The system uses backlighting with a Mercron HR-2048 system and a 2048-pixel line-scan camera, EG&G Reticon, LC1912, with a 90-mm lens, to acquire images with transverse resolutions as high as 0.05 mm for precise measurement of stem diameter. The maximum scan rate of the camera is 10,000 scans per second, which limits maximum longitudinal resolution to 0.5 mm. In demonstration trials, 100 seedlings each of two-year old Ponderosa pine and Douglas fir were measured four times each by the vision system and once each by four different quality control personnel. Machine diameter measurement variation was approximately one-fourth that of manual measurement. The coefficient of variation for the machine system was 1.4%, while that for manual measurement was 6.6% in diameter measurement. Presently, the system can inspect a 500 mm long seedling in approximately 0.25 seconds.

The possibility for automation of silverware washing is motivated by current successfully automated sorting and inspection in the food industry. For example, Simco/Ramic Corporation (1993) manufactures and markets a variable high speed sorting system for wet or dry foods. Examples of successful applications include the inspection and sorting of fruits, vegetables, nuts, potato chips, and even recycled plastic flakes. This system employs a full-color camera, and with high productivity, yields reliably consistent good product in food with up to 40% defects. For example, french fries can be processed at 30,000 pounds per hour, and plastic flakes can be handled at 5,000 pounds per hour, which is about 67% of capacity. In spite of the success of automated inspection and sorting of food items, there appears to be no such reliable, cost-effective system in use today for the inspection and sorting of silverware, or for that matter, any commercially washed dish pieces. For example, Hobart (1995), one of the leading food equipment firms, manufactures a state-of-the-art commercial dishwasher incorporating labor-saving automation for dishroom operations. In spite of Hobart's labeling this system a "Fully Automatic Warewahing System", with capability to sort several kinds of chinaware, it cannot inspect or sort silverware. It can, however, separate bulk silverware from trays.

The Design Problem

We assume for a prototype design that the silverware pieces are collected in a batch container with four kinds of silverware: butter knife, dinner fork, teaspoon, and soup spoon. Dimensions of these pieces as used in this study are given in Table I. The input to our automated system will be a container of mixed, washed silverware up to a maximum of 280 pieces for a prototype device. This capacity would allow 2800 silverware pieces to be sorted in 10 batches during a two-hour washing shift. The completed system would

TABLE I

DIMENSIONS OF SILVERWARE IN THIS STUDY

	Width (in.)	Height (in.)
Butter Knife	3/4	8-1/2
Dinner Fork	1	7-1/2
Teaspoon	1-1/4	6
Soup Spoon	1-1/2	5-1/2

include all material handling, classification, inspection, and sorting means to sort and deliver the silverware into six bins, one each for clean knives, forks, spoons, and soup spoons, one bin for mixed unclean pieces; and one bin for unrecognized pieces.

In order to handle a production rate of 1400 silverware pieces per hour (23 pieces/min.), which is the projected maximum for our target 700 bed hospital described earlier in this section, the material handling, classification, inspection, and sorting processes must be fast and efficient. For machine vision implementation of classification and inspection, there will likely be insufficient time to employ pattern matching algorithms for silverware pieces in mixed batches. It is more likely that much faster algorithms would be required such as feature characteristic identification, and that these would require silverware pieces to be separated from each other, and probably oriented in a preferred direction. Furthermore, the speed required will likely preclude robotic arm "pick and place" operations to either remove individual pieces from a mixed batch (assuming a vision system could handle identification) or to handle individual pieces once they have been separated, classified, and inspected. Even if a robotic arm could pick up several pieces of silverware at a time, it remains unlikely that with current technology such an arm could handle the require production rate. A faster, and probably less complex sorting mechanism is needed.

As design goals for our proposed system, we use the rate derived above, rounded up to 25 silverware pieces per minute, with each piece having maximum dimensions no more than 9 inches long, 2 inches wide and 1 inch thick. Using state-of-the-art CCD camera technology with at least a 2,048 pixel array, we target a detection rate of 97% of all dirty areas as small as 1 mm × 1 mm, similar to that of the SPECTRA-SORT SYSTEM of the Simco/Ramic Corporation (1993). For complete automation, the system should be capable of feeding mixed, batched silverware pieces to a separator, separating pieces such that they are non-touching and non-overlapping, orienting each piece in a prescribed position, sorting and inspecting each piece, and separating each piece into an appropriate bin. The system should also be capable of modification such that prescribed different pieces could be bundled and packaged together.

Objectives

From our design considerations, it appears that a mechanical device is needed that separates and orients silverware pieces in order that a subsequent machine vision system may quickly classify and inspect them. Following this, means would be needed to employ the machine vision classification signal to sort pieces into the various bins.

This thesis concentrates on the separation of silverware pieces before processing by machine vision and subsequent operations. As such, this work addresses only material handling issues, leaving inspection, sorting, and classification for subsequent investigations.

The process of the design and the results of experiments will be addressed in the following chapters. Chapter II introduces some initial ideas and experiments with several separator concepts. In Chapter III, the design of a mechanism to implement the selected concept will be discussed. The design of a feeding mechanism, which is used to feed the separator, will be discussed in Chapter IV. Experimental results are presented in Chapter V. Chapter VI gives conclusions and recommendations.

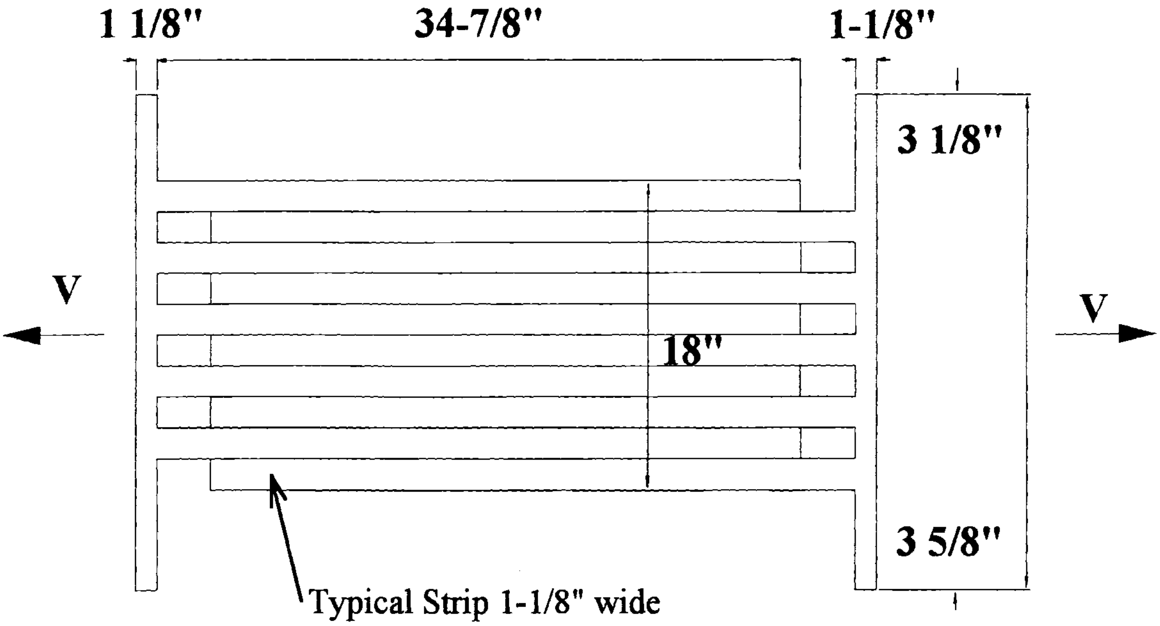
CHAPTER II

INITIAL EXPERIMENTS ON SEPARATION OF SILVERWARE

To address the problem of separating individual pieces from batches of mixed silverware, several brainstorming sessions with other researchers were used to produce ideas. Four early ideas seemed worthy of simple trials: (1) Alternately Moving Strip Conveying (AMSC); (2) Hindered Vertical Dropping (HVD); (3)Non-Magnetic Lift Conveying (NMLC); and (4) Magnetic Lift Conveying (MLC).

Alternately Moving Strip Conveying

Our first approach was to try alternately moving conveyor strips, consisting of several strips of adjoining belt or other material moving such that alternate strips traveled in opposite directions. It was thought that with appropriate widths of the strips and belt speeds, if a batch of silverware was metered onto the moving surfaces, individual pieces might be separated and aligned in the directions of motion of the strips. The concept is illustrated in Figure 2.1, in which the widths of alternately moving strips was to be slightly larger than the largest contact width of all silverware pieces. A simple implementation of this concept was constructed of narrow, parallel wood strips, in which every other strip was attached to a common " left manifold", and the alternate strips were attached to a "right manifold". As shown in the photograph in Figure 2.2, there were 5 strips each for the left and right manifolds, with each strip being 1-1/8 in. wide × 36 in. long. This simple implementation allowed us to test the concept by metering a batch of 70 pieces of mixed silverware onto the conveyor surface as the manifolds were pulled in opposite directions at



V = Velocity of Manifold Strip

Figure 2.1 Alternately Moving Strip Conveyor

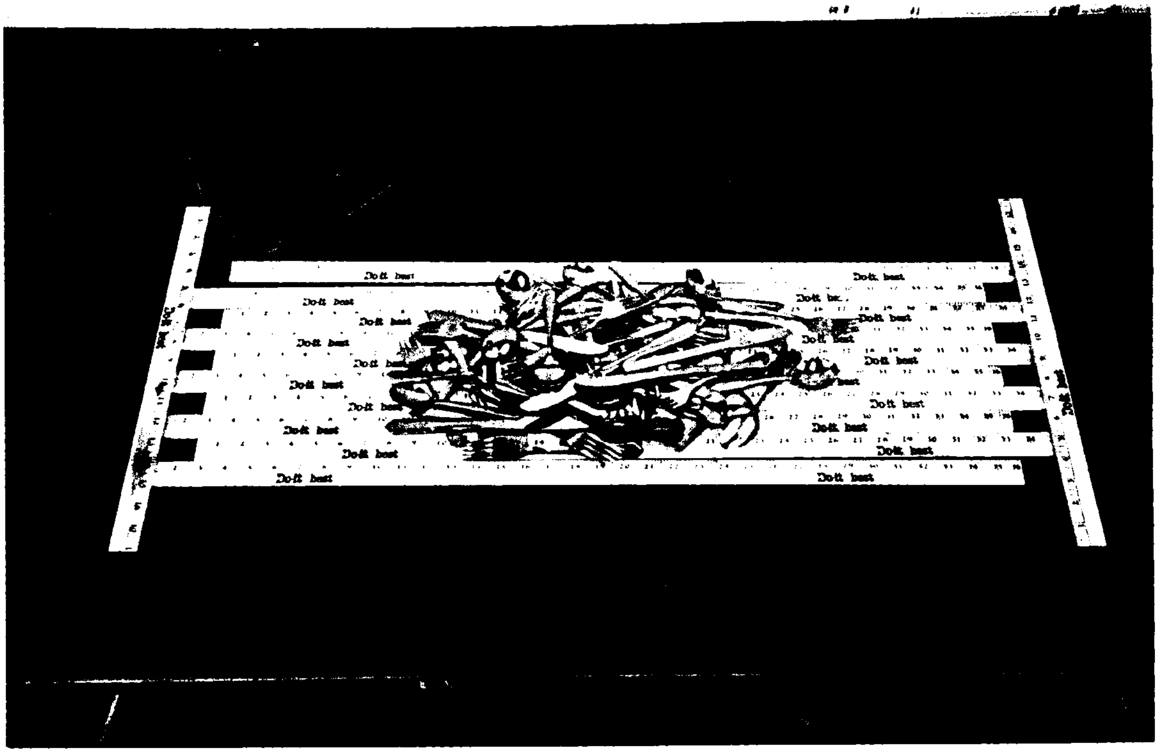


Figure 2.2 Alternately Moving Strip Conveyor

identical speeds. However, we were unable to find any combination of reasonable metering rates and conveyor speeds that yielded satisfactory results. The photograph in Figure 2.3 shows typical results. Silverware pieces invariably remained in contact with each other or did not separate longitudinally as expected. Moreover, we were unable to achieve consistently satisfactory longitudinal orientations. Numerous experiments with this simple device convinced us that we would encounter similar difficulties with other widths of moving strips, such that we abandoned this concept as viable.

Hindered Vertical Dropping

Our second idea was based on combining hindering, such as that of balls in a pin-ball machine, with a moving belt conveyor. We thought that if a mixed batch of silverware was metered into the top of a container tower, open at the top and bottom, and allowed to drop vertically through hindering means onto a moving conveyor belt, suitable separation might be achieved. We implemented this idea using commercially available 1/4 in. thick masonite pegboard to construct four box-like containers, stacked one upon the other, inside each of which we installed rows of PVC pipe in differing row geometries to serve as the hindering means. Four containers were chosen to make up the tower to allow flexibility in changing the hindering means throughout the height of the tower. Figure 2.4 illustrates this concept, showing container dimensions. After experimenting with several sizes of PVC pipe, we selected 2-3/8 in. OD pipe as having the most promise for hindering the drop of silverware. Figure 2.5 shows an end view of one of the row geometries we selected for trial. Each segment of pipe in a row was fastened to the container sides by hanging it from screws placed through appropriate pegboard holes. This allowed flexibility to quickly change row geometry.

Several configurations of row geometry were tried, with that shown in Figure 2.5 giving the best results, even though these results were unsatisfactory. The stacked tower

Figure 2.3 Result of Alternately Moving Strip Conveyor

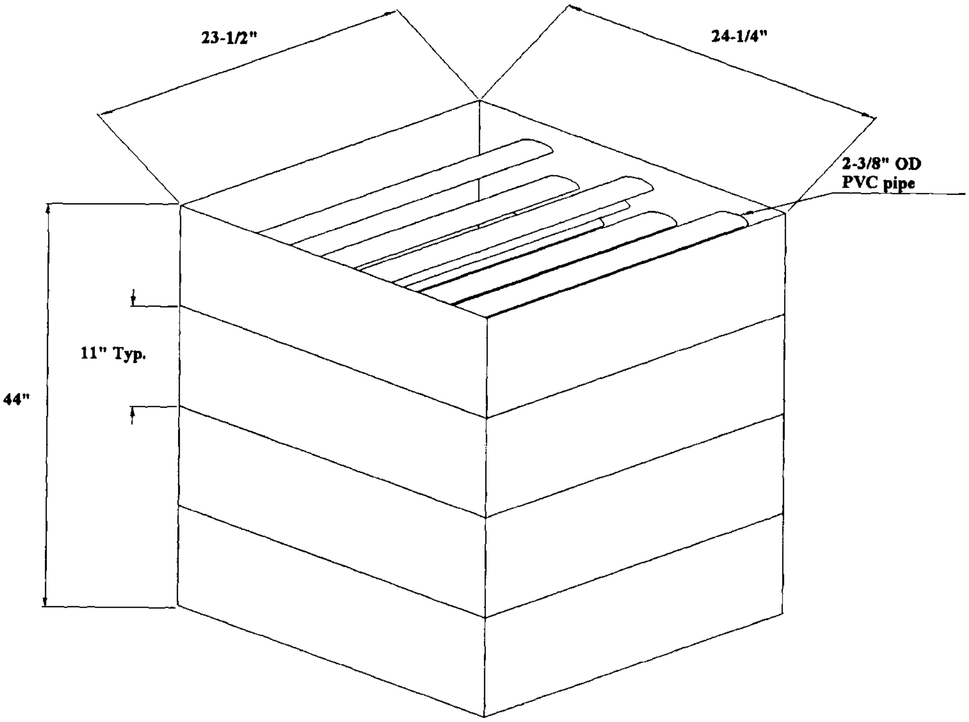


Figure 2.4 Hindered Vertical Dropping

was placed over a moving, variable-speed conveyor belt, and a batch of 70 mixed pieces of silverware was first "dumped" and later more slowly metered into the top of the tower from a bulk container. All tests were run with the conveyor moving at 13 ft./min., which is the rate of dish rack movement in the aforementioned hospital dishroom. It was felt that we could simulate different conveyor speeds by varying the rate at which we metered silverware into the top of the container. The photograph in Figure 2.6 shows the tower with silverware being placed into the top. Over a number of runs, we found that the silverware exiting the bottom of the tower onto the moving conveyor belt exhibited some separation, although far less than desired, but the orientation of individual pieces was random. To improve the operation and provide consistent orientation of silverware pieces on the conveyor belt, we replaced the hindering rows in the bottom tower box with sloping plywood panels converging to slots at the bottom, as illustrated in Figure 2.7, with panel dimensions and placement as indicated. After several more trials, we discovered no meaningful difference in results when only one hindering box was used above the panel box, instead of three. Accordingly, we eliminated two intermediate hindering boxes for the remaining trials. By setting the panel box such that the exit panel slots were oriented in the direction of conveyor motion and adjusting the clearance between the panel exit slots and the conveyor belt to values less than the length of the shortest piece of silverware, we obtained much improved orientation of the silverware. However, after numerous trials, we were unable to achieve satisfactory and consistent separation of silverware pieces. The photograph in Figure 2.8 shows an example of our best results. We concluded that regardless of the hindering combinations used, for any feasible metering rate of silverware introduced into the top of the device, there would be insufficient vertical separation of different pieces of silverware to give this concept much promise.

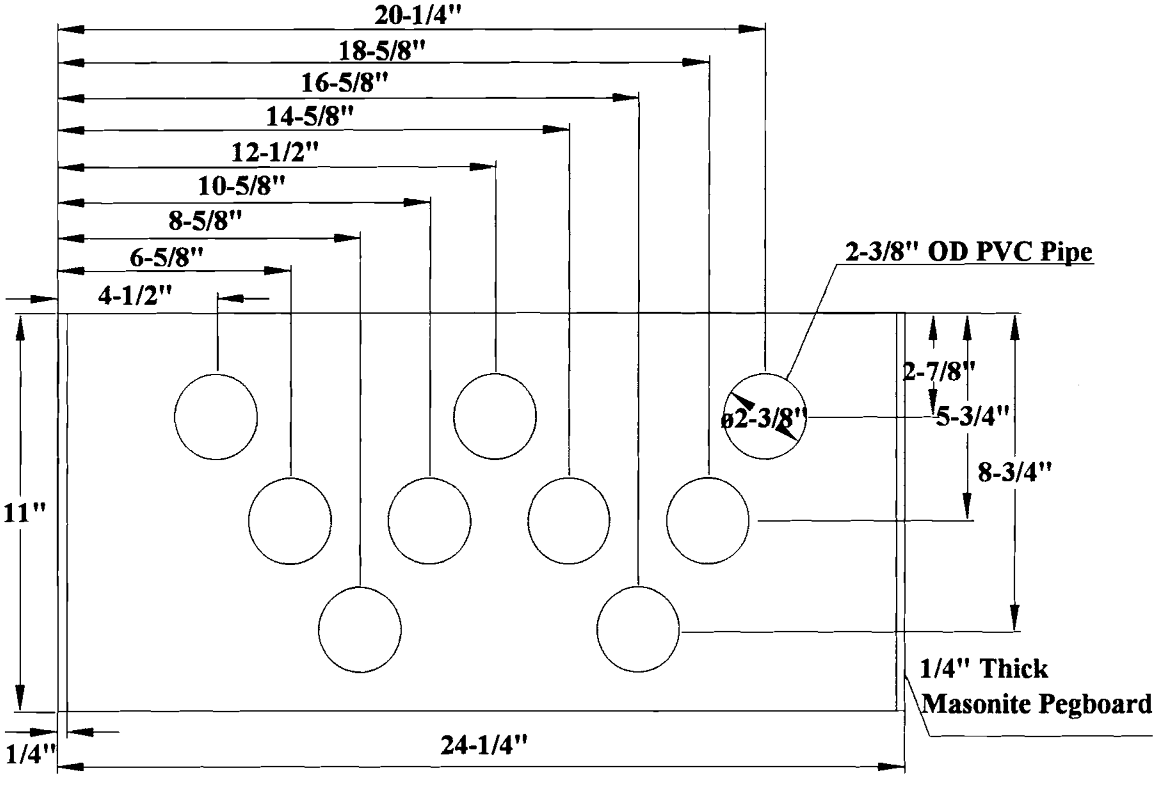


Figure 2.5 End View of One of the Row Geometries for Hindered Vertical Dropping

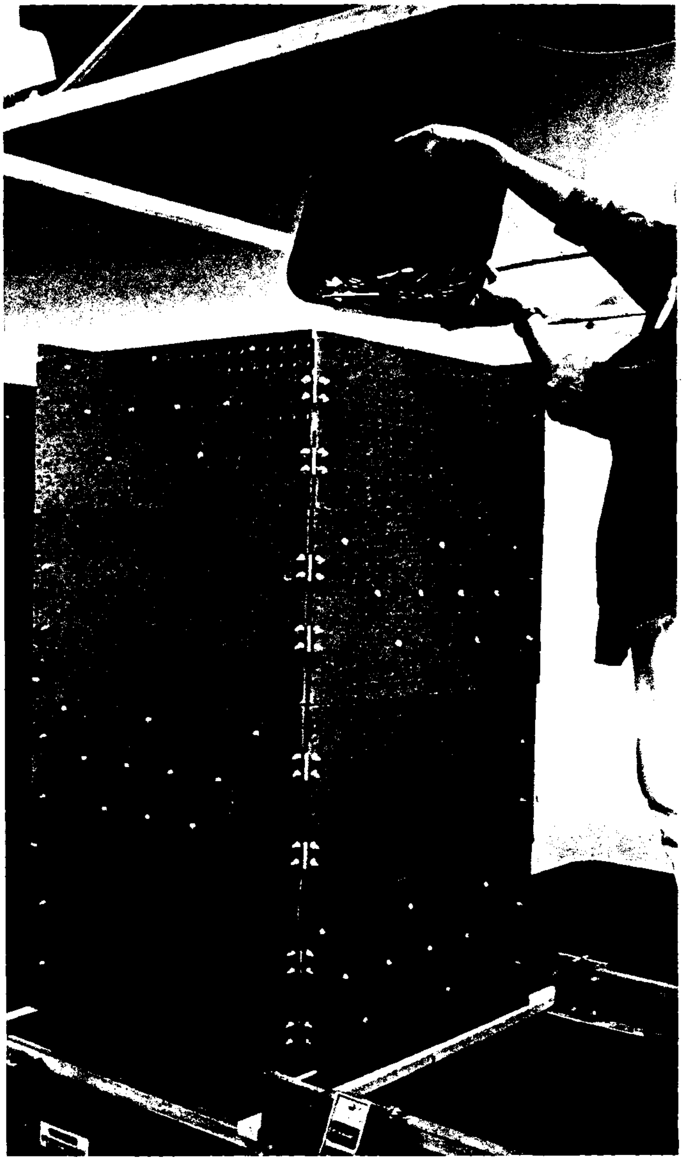


Figure 2.6 Hindered Vertical Dropping Tower with Silverware Being Placed into the Top

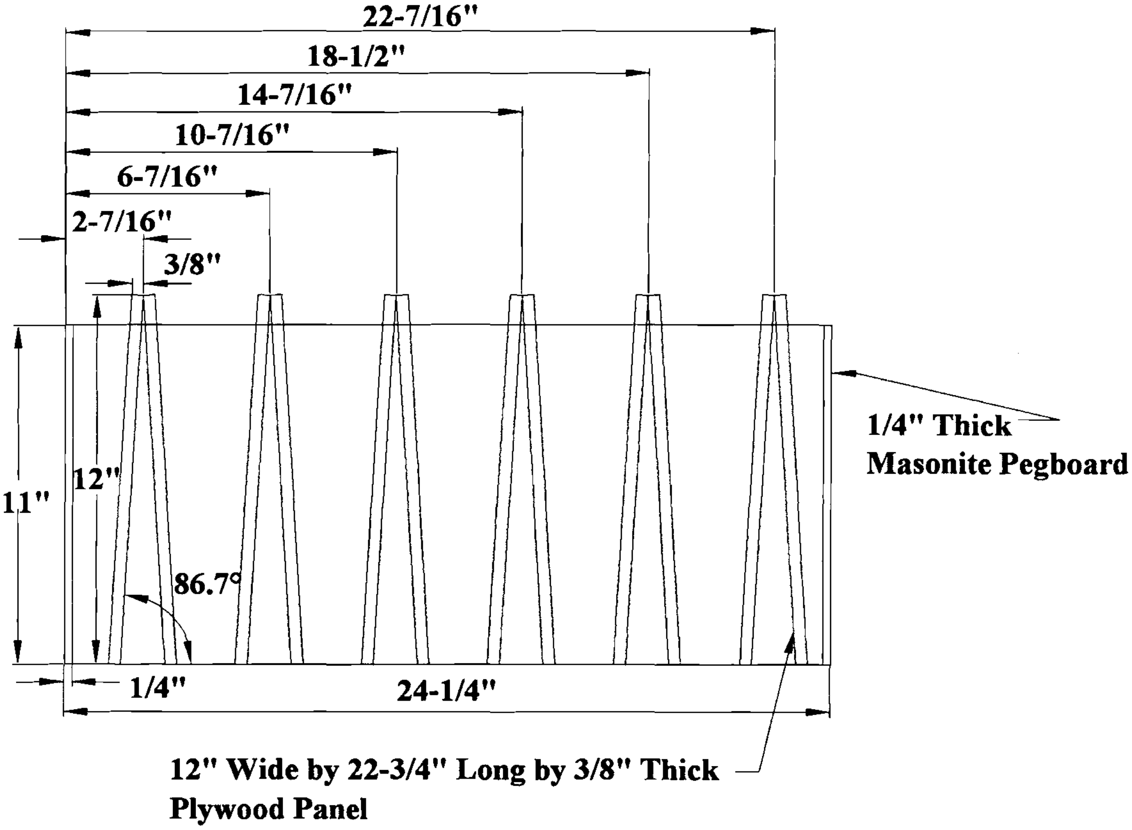


Figure 2.7 Sloping Plywood Panels Converging to Slots at the Bottom in the Bottom Tower Box

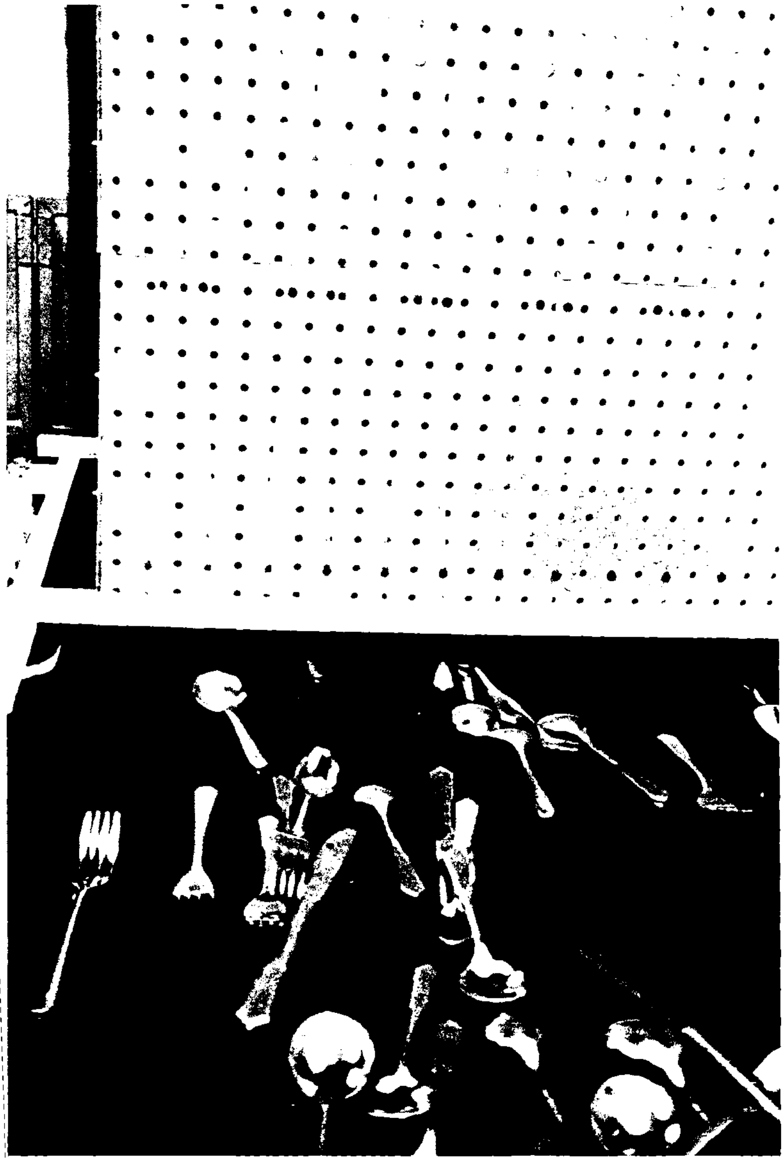


Figure 2.8 Result of Hindered Vertical Dropping with the Sloping Plywood Panels

Non-Magnetic Lift Conveying

Our third idea employed a non-magnetic lift conveyor, consisting of a belt conveyor having lifting ledges attached to its surface. We expected that the ledges might pick up individual silverware pieces by placing the feed end of the conveyor into a batch container filled with mixed silverware, setting the conveyor at an appropriate angle upward from horizontal, and adjusting the conveyor speed to some suitable value. From observations made during trials with the first two experiments, these observations suggested that we needed a "metering" mechanism to handle pieces one by one. We implemented this idea by using a wood conveyor frame made from 3/4 in. thick plywood, 3-1/2 in. wide × 31 in. long. To this frame we remounted drive and follower rotating shafts made from 1-3/8 in. OD PVC pipe separated 28 in. center to center with 12 in. between the wood conveyor frame side plates. For the conveyor belt we used plastic mesh sheet 10-1/2 in. wide × 60 in. long, formed into a continuous belt around the shafts by fastening the ends to one of the wood lifting ledges. Eight finishing nails were driven equally spaced around the circumferences of both ends of the two shafts, with approximately 1/8 in. of each nail exposed to serve as sprockets to engage the meshes in the belt. A hand crank was then fastened to the upper drive roller to provide rotating power to the belt. We screwed 12 pieces of 1/2 in. wide × 3/4 in. thick × 9-1/4 in. long wood ledges to the plastic mesh belt with a spacing of 1 ledge every 4-/2 in. This spacing was chosen to be slightly shorter than the length of the shortest silverware piece. The size of the ledge was chosen such that it could carry no more than one piece of silverware. The concept is shown in the photograph in Figure 2.9. We set the conveyor at various angles up from horizontal, put the bottom end into the batch container filled with the silverware, and rotated the crank. After experimenting with several different angles and conveyor speeds, we selected 70 degrees and 6 ft./min. conveyor speed as

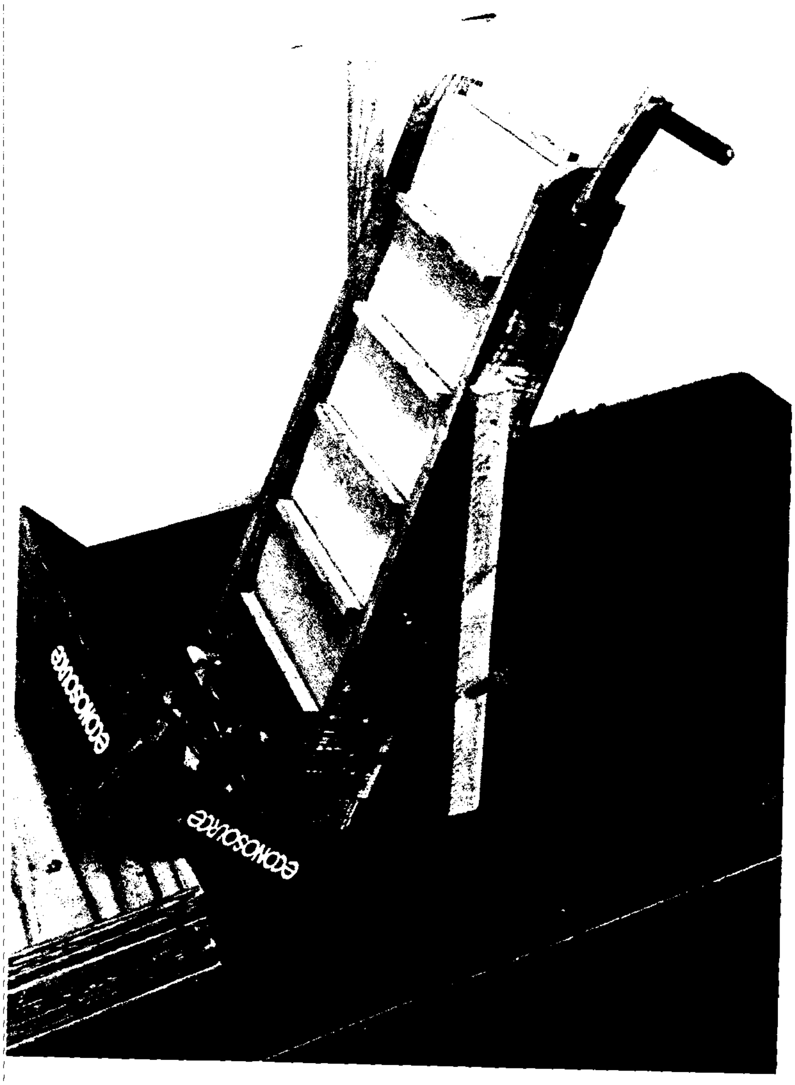


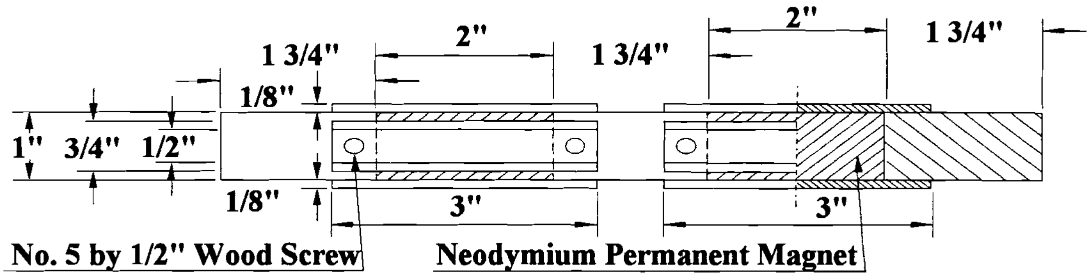
Figure 2.9 Non-Magnetic Lift Conveyor

Figure 2.10 Result of Non-Magnetic Lift Conveyor

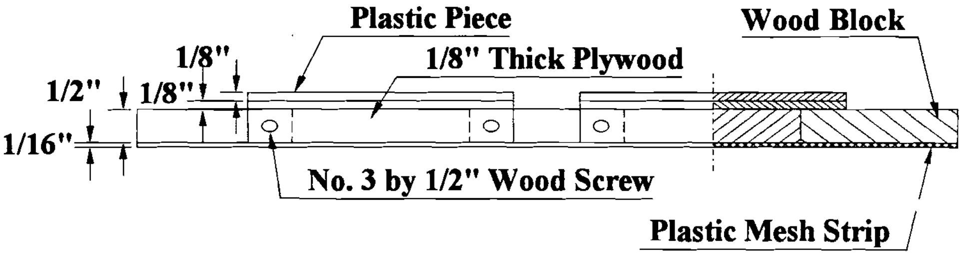
having the most promise for lifting single silverware pieces from the batch. The photograph in Figure 2.10 shows typical results. Numerous ledges failed to pick up the silverware. For those ledges that did, many had silverware fall off before being conveyed to the top discharge point. We concluded that regardless of the angle and speed used, individual silverware pieces could not consistently be extracted and conveyed. While vibrating the feeder batch box improved results, the improvement was judged insufficient to continue with this approach. However, these experiments suggested that conveying might work if means were employed to pick up and securely hold silverware as it was conveyed to a discharge point.

Magnetic Lift Conveying

While most stainless steels are non-magnetic, the stainless steels used in commercial silverware contain 13% chromium and a small amount of nickel, such that such steels are magnetic (Kotschevar and Terrell, 1985; Ryan, 1994). This property is exploited by Hobart Corporation in its "Fully Automatic Warewashing System" (1995), which employs a large rotating drum carrying strip magnets which move beneath a stationary circular plastic sheet to pick up magnetic silverware pieces from trays moving under the plastic sheet. Adapting from Hobart's implementation, our final idea was to use magnets in place of the lifting ledges described above, converting to a magnetic lift conveyor. The magnets would be mounted in wood strips fastened in place of the ledges, and would move under a stiff plastic sheet fastened over the top edges of the frame. Silverware attracted by the magnets would slide on top of the plastic cover, following the moving magnet underneath. This would allow silverware pieces to be easily discharged when the magnets rotated away from the sheet as they rounded the drive roller. We planned to control the magnetic attractive force by controlling the clearance between the plastic cover and the magnet such that by combining this with conveyor speed control, we might be able to pick up individual silverware pieces and convey each piece separately to a discharge point. Accordingly, we changed the lifting ledges on the conveyor used in the previous experiment to magnetic pieces mounted in wood strips. As shown in Figure 2.11 each row of a wood-magnet strip consisted of three wood blocks 1-3/4 inches long × 1 in. wide × 1/2 in. thick and two Neodymium permanent magnets 2 in. long × 1 in. wide × 1/2 in. thick. The two magnets were placed between the three wood blocks, such that they were 1-3/4 inches apart; they were secured by a plastic mesh strip at the bottom and by two plastic pieces at the top, as shown in Figure 2.11. Initial experiments with this device gave promising results, but the plastic mesh conveyor and wood construction was not sufficiently substantial to allow extensive testing, which we felt was warranted. Accordingly, we decided to construct a new prototype with aluminum replacing the wood, replacing the hand crank powering the conveyor with a variable-speed DC motor drive, and chain drives and sprockets replacing the plastic mesh. Details on design and material selection for this sturdier prototype are given in Chapter III, but in order to present results that replicated results obtained with the wood construction, we briefly present some initial results here. The photograph in Figure 2.12 depicts the new and sturdier magnetic lift conveyor, which has overall dimensions of 33-1/2 in. long × 11-5/8 in. wide × 5-5/8 in. deep. The new strips carrying the magnets were changed to aluminum strips 8 in. long × 1-1/4 in. wide × 1/4 in. thick, each containing a shallow groove to hold the magnets, 8 in. long × 1 in. wide × 1/16 in. deep. Two magnets are set in each groove 2 in. apart, secured by four round-head machine screws using the edge of the head to engage the top edge of the magnet. The aluminum strips carrying the magnets were carried by two parallel roller drive chains on sprockets driven by a variable speed DC motor. We set the conveyor at various angles with the horizontal and placed the feed end into a batch container filled with mixed silverware pieces. As the aluminum-magnet strips moved under the plastic sheet from feed to discharge, silverware pieces were pulled by magnet force along the



TOP VIEW



SIDE VIEW

Figure 2.11 Wood-Magnet Ledge

plastic and carried to the discharge end. At the discharge end of the conveyor, the magnets rotate away from the plastic sheet and return to the feed end of the conveyor. This causes the silverware pieces to loose magnetic attraction, such that by gravity they slide along the plastic sheet to discharge (and the next stage in the sorting process). Typically, after a few pieces of silverware were selected and conveyed to discharge, a jam occurred in the batch container, such that more pieces could not be picked up. This problem could be alleviated by manually vibrating the batch container, but without metering control, multiple silverware pieces would be picked up, as shown in Figure 2.13.

We concluded that the magnetic lift conveyor had significant promise, provided we could design and implement a suitable feeding mechanism for the batched silverware. In the following chapters we discuss the design and construction of such a device, together with the design and construction of the conveyor.

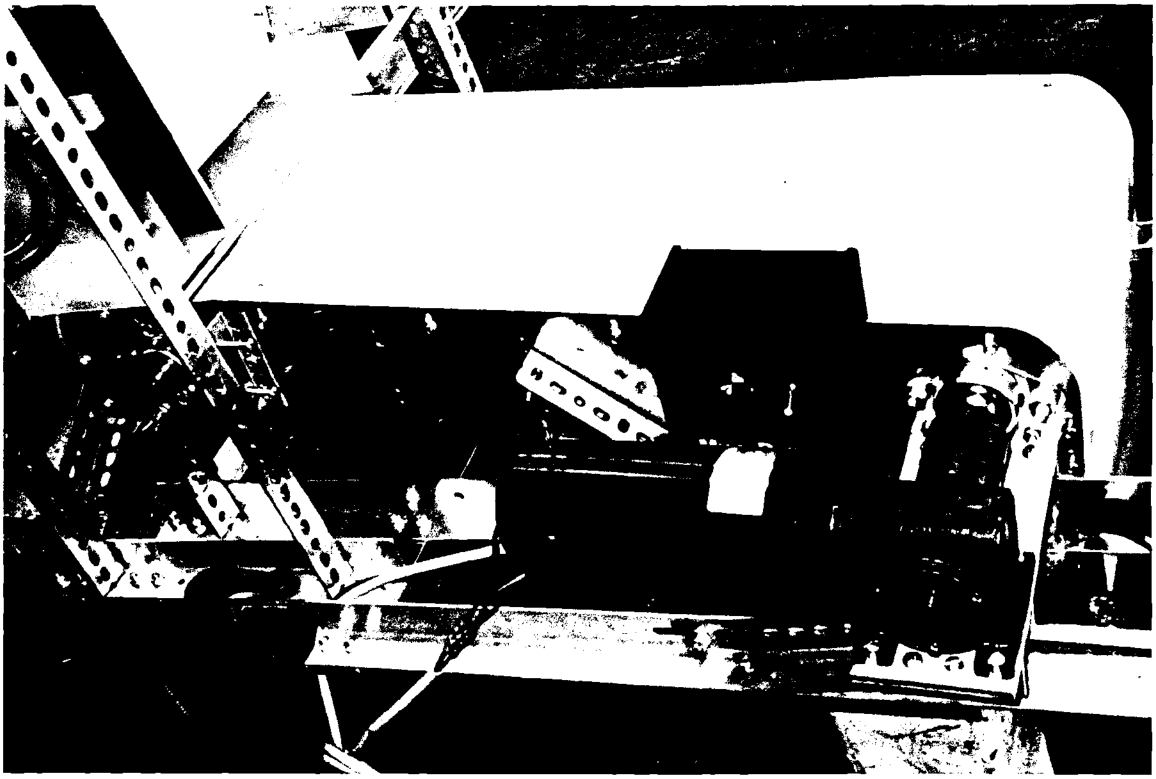


Figure 2.12 Aluminum Prototype of Magnetic Lift Conveyor

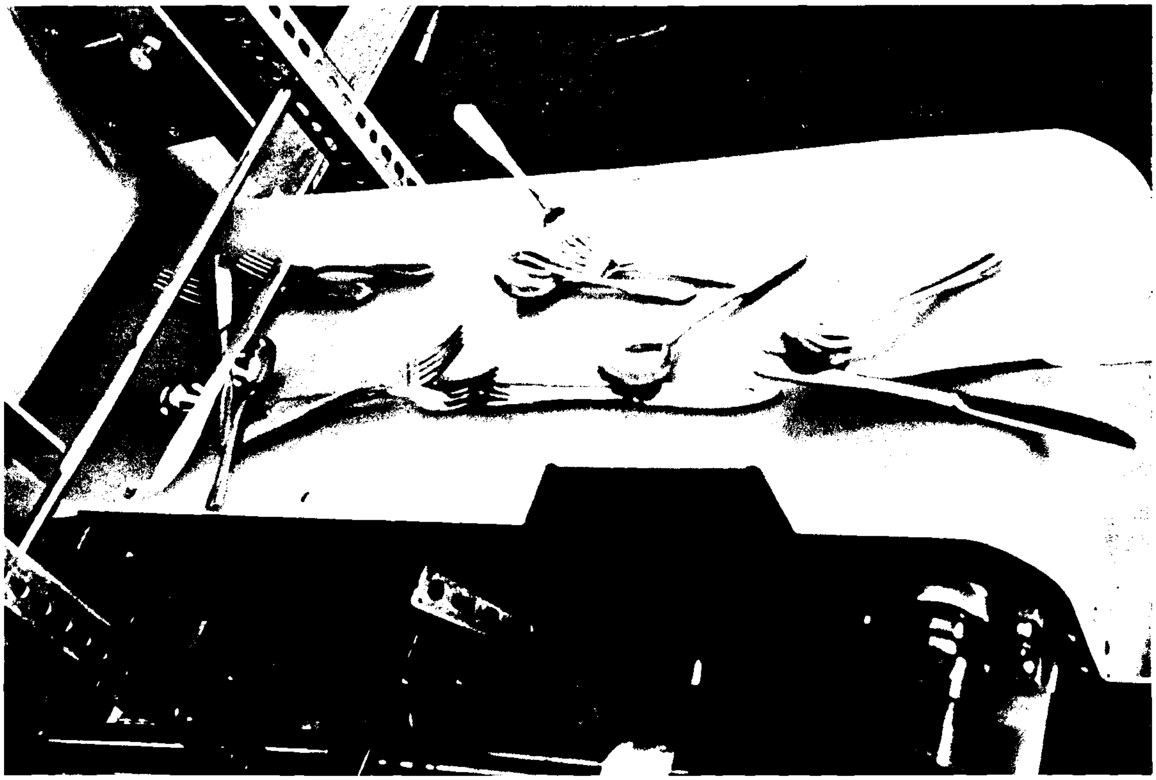


Figure 2.13 Results of Magnetic Lift Conveying without Metering Control

CHAPTER III

DESIGN OF SELECTED SEPARATOR

System Concept

Following the last of our initial experiments discussed in Chapter II, we elected to design and construct a magnetic lift conveyor. The width of the conveyor was determined by our desire to handle single pieces of silverware of the longest dimension (butter knife) laying perpendicular to the direction of magnet motion. Since the knife being used was 8-1/2 in. long, we allowed a small lateral tolerance and chose the active conveying surface to be 11-5/8 in. wide. Ultimately, to handle support and drive mechanisms, the overall width of the conveyor become 20 in. In order to reduce size and weight of the conveyor, as well as total silverware drag force needed from the drive motor, we elected to maintain the length of the conveyor small. However, for experimental purposes, we needed suitable length to observe the action of various silverware pieces as they were conveyed. As a trade-off, we selected a longitudinal conveying length of 26-1/4 in. Allowing for drive sprocket dimension and other structural components, the overall length of the conveyor became 33-1/4 in. The depth of the conveyor was also kept small to minimize size and weight. The overall depth of 5-5/8 in. was determined by the diameter of the drive sprockets and the thicknesses of the aluminum-magnetic strips and plastic cover sheet. The details of the final design of the conveyor, presented in Appendix A, were determined largely by trial and error once the basic concept was established. While discussion of most of these details is unimportant to the central purpose of this thesis, some of the key design considerations and material selection problems deserve discussion. This is provided in what follows.

Materials for Conveyor Surface

Following the basic idea used by the Hobart Corporation (1995), we needed a surface along which silverware pieces could slide while being pulled along by magnets underneath. The basic requirements are that the material should be: (1) slick enough for low friction sliding of silverware pieces; (2) tough enough to resist wear; (3) flexible such that it could be easily formed around curved ends of the sprocket drives at feed and discharge ends; and (4) stiff enough to provide support for the silverware. Various types of plastic seemed appropriate for this application, so we examined four types: ABS(Acrylonitrile-Butadiene-Styrene), LEXAN® polycarbonate with Margard®, UHMWPE(Ultrahigh Molecular Weight Polyethylene), and HDPE(High-Density Polyethylene). While we were aware that Hobart Corporation had used Simona Olefin Polymer No. PP-BWST(Rowley, 1994), we wished to examine for ourselves what might be the best choice.

ABS is formed by combining three monomers - Acrylonitrile, Butadiene, and Styrene. Each monomer contributes to the final ABS product. Acrylonitrile contributes heat resistance, high strength, and chemical resistance. Butadiene provides impact strength, toughness, and low temperature property retention. Styrene, on the other hand, gives gloss, rigidity, and processability. ABS has (1) good to excellent toughness, (2) high mechanical strength and (3) moderate price (The handbook from Regal Plastics Supply Company, 1994).

LEXAN® Polycarbonate with Margard® offers a good combination of abrasion resistance and toughness for locations where clarity and aesthetics must be maintained

(The handbook from Regal Plastics Supply Company, 1994). Its improved, state-of-the-art coating is also guaranteed and makes Margard® sheet the most abrasion-resistant polycarbonate glazing product available. Margard® sheet is ideal for flat glazing in schools, public buildings, storefronts, shopping malls or wherever clarity plus safety and security are required.

The major advantages of polyethylenes are: low cost, light weight, excellent chemical resistance, low moisture absorption, good impact strength, excellent low temperature properties, excellent resistance to gamma rays in atomic radiation, low coefficient of friction, ease of fabrication, and non-toxicity (The handbook from Regal Plastics Supply Company, 1994). HDPE is characterized by its opacity, chemical inertness, toughness at both low and high temperatures, chemical resistance, and moisture barrier and electrical-insulating properties (ASM International, 1988); UHMWPE has both the highest abrasion resistance and highest impact strength of any plastic. Combined with abrasion resistance and toughness, the low coefficient of friction of UHMWPE yields a self-lubricating, non-stick surface. Static and dynamic coefficients of friction are significantly lower than steel and most plastic materials (ASM International, 1988).

Dropping pieces of ABS and HDPE, from moderate heights, will break HDPE, but not ABS. However, scratch resistance is more important for our application than impact strength. Although ABS is relatively inexpensive, its mechanical properties are somewhat invariant with low temperature heat, which makes it difficult to bend. LEXAN® with Margard® has high wear resistance and impact strength, but is easily scratched, with scratches visible. Scratches on HDPE for the same scratching mechanism typically remain invisible. Similar to ABS, LEXAN® with Margard® is heat resistant. It is used primarily for security purposes, and the price per pound is three times that of HDPE. Because of its scratch susceptibility and high cost, it appears inappropriate for our application (Holmes, 1994; Welch, 1994). Hobart's "Fully Automatic Warewashing Systems" (The catalog from Hobart Corporation, 1995) uses Simona Olefin Polymer No. PP-BWST for the cover

over its magnet drum, which picks up silverware from a tray (Rowley, 1994). Polyethylene, discussed above, is one member of the family of Olefin Polymers.

Because of its ready availability and relatively low cost, we decided to use HDPE for our prototype machine, realizing that for a production machine we may upgrade to Simona Olefin or UHMWPE. We selected 1/8 in. thick HDPE sheet, at a cost of $35.62 per sheet with dimensions 8 ft. long × 4 ft. wide. Typical properties of HDPE are given in Appendix B. We cut from this sheet a piece 11-5/8 in. wide × 48 in. long. By using a heat gun with dual temperature selections of 750°F and 1000°F, we could easily bend this piece at its ends through 90° of turn with a 2.67 in. radius, as required by our design.

Selection of Magnets

For our first experiments, we tried flexible ferrite permanent magnetic strips, purchased in rolls and cut to length, attaching them to the wood ledges on the first conveyor described in Chapter II. However, the magnetic force was insufficient to pull silverware along the plastic cover. While we briefly considered using electro-magnetic means to attract silverware pieces, we felt implementation would be excessively complex and expensive. We then tried three kinds of commercially available permanent magnets: alnico, ceramic, and rare earth magnets. We visited a permanent-magnet supply and manufacturing firm, Bunting Magnetics Company in Newton, KS, where we experimented with each of the 3 types in various sizes with our silverware pieces. Such magnets are characterized by their holding force and their energy product, which is the product of demagnetizing force (oersteds) and normal induction (gauss). Alnico magnets derive their magnetic properties and their name from their main constituents - aluminum, nickel, and cobalt. They have the widest range of temperature stability of any standard magnetic material. Other characteristics include high induction, as well as relatively high energy product. Manufacture is by sintering or casting. Alnico magnets are the best choice for applications exposed to operating temperatures above 400°F; at 1600°F they become completely demagnetized. Depending upon the grade and type of manufacture, alnico magnets have energy products ranging from 1.5 to 6.0 MGO (mega gauss oersteds). Alnico magnets are hard and brittle, requiring skillful machining on specialized equipment.

Ceramic magnets have become the most widely specified magnetic materials for industrial use, primarily in 3 grades: 1, 5, and 8. Low cost, light weight, a relatively high energy product, and good resistance to demagnetization account for their widespread use. Ceramic magnets are sintered from barium or strontium ferrite. They retain about 45% of their room-temperature magnetic specifications at 350°F. Degradation with increasing temperature is nearly linear, and changes in magnetization are essentially reversible up to approximately 840°F, at which temperature ceramic magnets become completely demagnetized. Depending upon grade, these magnets range in energy product from 1 to 3.6 MGO. Ceramic magnetic material is very hard and brittle and should be cut before it is magnetized.

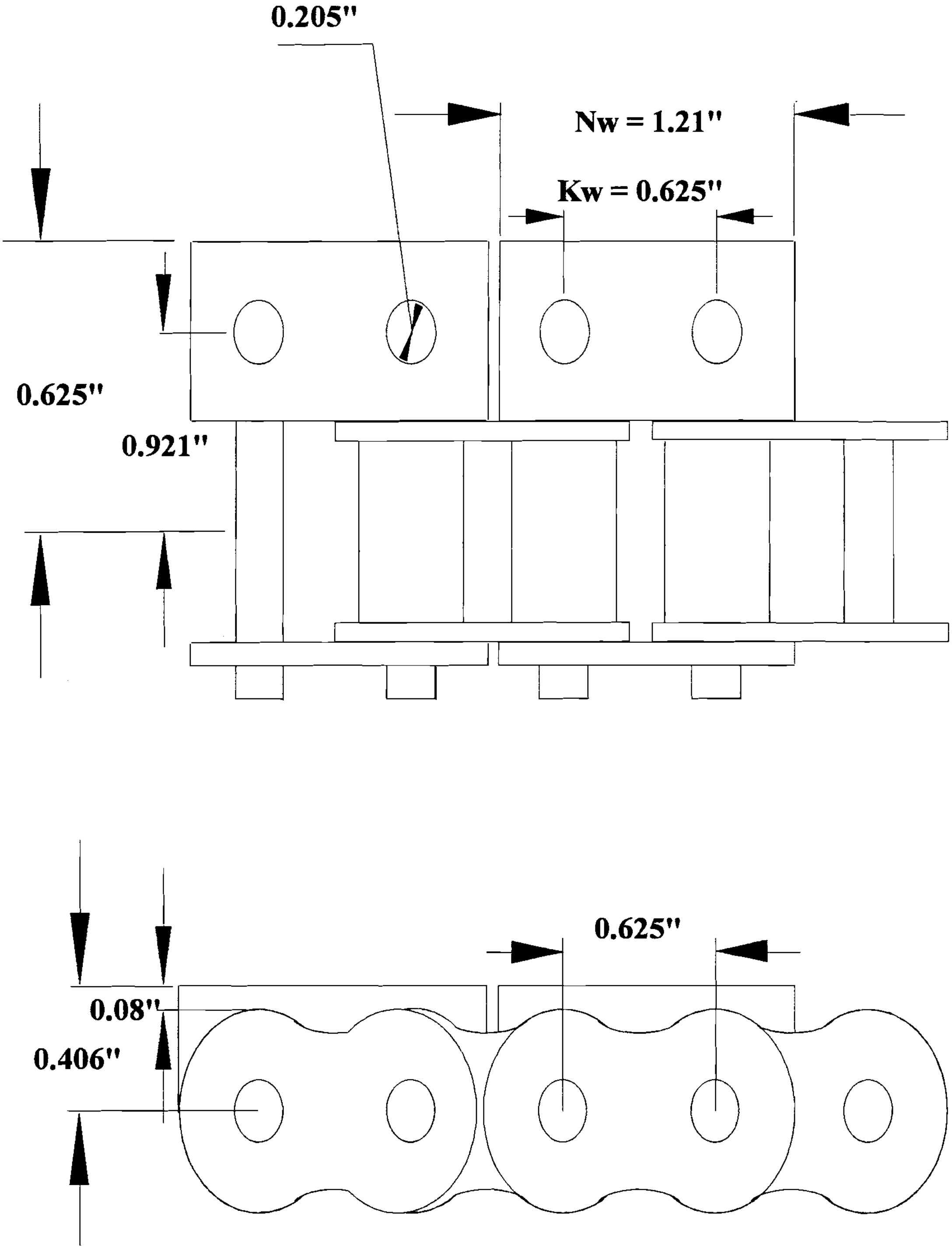
Rare earth magnets offer the highest of holding forces required in many of today's more demanding consumer and industrial applications. These magnets represent the most powerful advance in permanent magnetic materials, with neodymium, the most commonly used alloy used together with iron and boron. These neodymium magnets are the latest development in high-energy magnet technology. They are manufactured from non-critical raw materials and priced to be the most cost-effective high energy magnets on the market. Neodymium is a sintered material that offers superior mechanical properties, with use restricted to operating temperatures below 180°F. Because of their magnetic strength, neodymium magnets must be handled with special care (The catalog from Bunting Magnetics Co., 1993).

In our tests at Bunting Magnetics Company, we found that neodymium magnets, although the most expensive, gave us the greatest flexibility in adjusting pick-up forces on silverware over the widest force range. This was due to their superior contact force and the fact that we could decrease the effective force on silverware by increasing clearance between the magnets and the plastic cover on our conveyor. High temperature is of no concern in our application. The magnets we chose were neodymium 27 black shape (Catalog No. NEB-2712, The catalog from Bunting Magnetics Co., 1993), with dimensions 1/2 in. thick × 1 in. wide × 2 in. long. Each magnet weighed 0.269 lbs. (Hall and Suderman, 1994). Magnet specifications and demagnetization curves for the three types of magnets discussed above are given in Appendix C.

For a total of 12 aluminum strips, two magnets were secured to each strip, 8 in. long × 1 1/4 in. wide × 1/4 in. thick, with a length-wise groove to hold the magnets, 8 in. long × 1 in. wide × 1/16 in. deep. Two magnets were set in the groove 2 in. apart and secured by four round-head machine screws using the edge of the head to engage the top edge of the magnet. Two magnets spaced 2 in. apart were used because this was the minimum necessary to securely hold a silverware piece perpendicular to the direction of conveyor motion.

Selection of the Magnet Drive

Having selected magnets to attract silverware pieces and convey them along the plastic surface, we needed means to mount and move the magnets. Following practice used by applications engineers at Bunting Magnetics Company, we selected parallel chain drivers that could be purchased with 90° angle-shaped attachments placed at specified internals for attaching magnet-carrying strips spanning the distance between the parallel chains. Each chain has a drive sprocket at the discharge end and a follower sprocket at the feed end of the conveyor. To guide each chain along its path just under the plastic conveyor surface, we selected polyethylene chain guides which would retain the magnets at a pre-selected distance below the conveyor surface. As shown in Figure 3.1, we

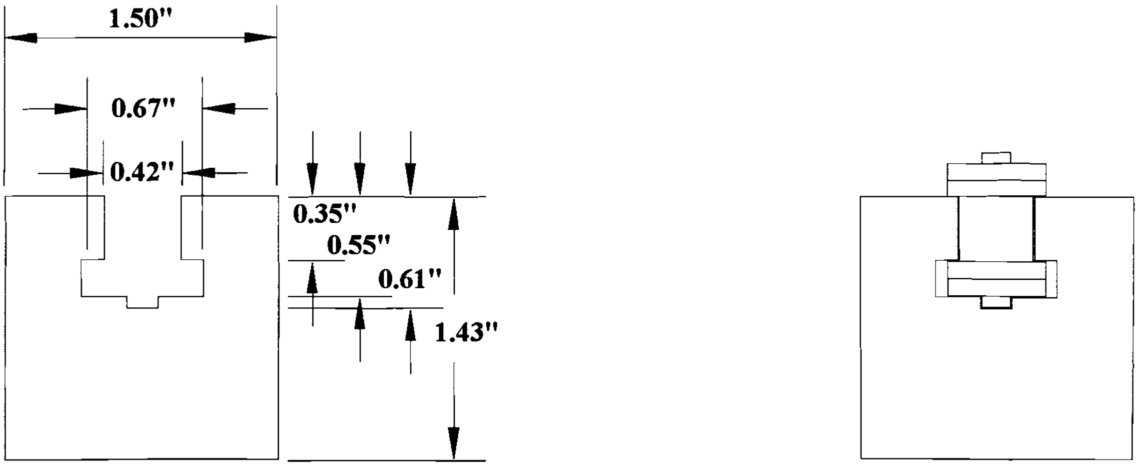


TSUBAKI RS50-1 WA2 Attachment

Figure 3.1 Selected Attachment Chain

selected a chain with a fastening attachment having two holes in a 90° angle mounted on the chain.

To specify the chain, we needed to know the nominal operating speed. We determined this by assuming that we could handle as many pieces of silverware as our design goal if the conveyor moved at 2 ft./sec., yielding a linear nominal speed of 120 ft./min. Two other needed parameters are Kw (the distance between the holes on the attachment) and Nw (the width of the attachment). By knowing the dimensions of our aluminum magnetic carrying strip (8 in. × 1-1/4 in. × 1-1/8 in.), we could determine that $Nw \geq 1$ in. and $Kw < 1$ in. would be required. Using the chain catalog from U.S. Tsubaki, Inc. (1994), we selected chain No. RS50, with $Nw = 1.21$ in. and $Kw = 0.625$ in. For our selected conveyor length of approximately 32 in., the pitch length of 0.625 in. for this chain dictated a chain length of 96 pitches. The spacing between the aluminum strips, each carrying two magnets, was selected as 5 in. (in the direction of conveyor motion). This dimension was used because it was the largest length allowable to pick up the shortest piece of silverware oriented in a direction parallel with conveyor motion; this would allow an alternative in case perpendicular orientation was found inferior. Accordingly, we selected an angle attachment on the chain to be placed every 8 pitches. Because the plastic conveyor sheet covers the magnets, chain, and drive mechanism, we do not expect water from wet silverware to reach these elements. We can assume the operating temperature is at room temperature, and because loads are small, a special lubrication system is not required. With these conditions, a plain carbon steel chain is sufficient for our application. From this chain selection, we can decide the size of sprockets. We judged that a driving shaft of 1 in. diameter of plain carbon steel would be sufficiently strong to carry relatively light torque loads. In order to reduce weight, we selected a smaller diameter of 5/8 in. for the follower shaft. We chose an UHMWPE chain guide with cross section shown in Figure 3.2 to restrain the movement of the chain to the longitudinal direction.



SOLIDUR TIVAR ANSI Standard Roller Chain Guide, Profile K No. 50

Profile K Illustrated with Chain

Figure 3.2 Cross Section of Polyethylene Chain Guide

In summary, the chains we selected were two TSUBAKI RS50-1 8L WA2, each 96 pitches long. (The catalog from U.S. Tsubaki, Inc., 1994) The chains are set 9-1/2 in. apart in the conveyor. The sprockets are four TSUBAKI 50B12F, with 12 teeth, each having a keyway and two set screws (The catalog from U.S. Tsubaki, Inc., 1994). Two had a 5/8 in. bore size and two had a 1 in. bore. The UHMWPE chain guides were SOLIDUR TIVAR ANSI Standard Roller Chain Guide, Profile K No. 50 (The catalog from Menasha Corp., 1994). Each of the four guides were cut 22 in. long.

Selection of Chain Drive

We determined that experimental flexibility was needed to determine effects of various conveyor speeds. This suggested the best choice for a conveyor drive motor would be a variable speed DC gear motor having suitable speed and torque range. To minimize complexity, we desired a direct drive from the motor output shaft to the sprocket drive shaft. In the previous section we selected the average conveyor speed as

120 ft./min. Assuming that we might experiment with speeds up to twice this value, we selected 240 ft./min. as our desired maximum. With our selected sprocket pitch diameter of 2.415 in., this yielded a maximum drive shaft speed of 380 rpm. To determine the approximate torque, we performed a simple experiment. We measured the force to move the crank of the wood-magnetic prototype conveyor oriented vertically, with loads of silverware varying from 0 to a full load of 18 knives, with the butter knife being the heaviest piece. Knowing the radius of the crank and the fact that the spring scale used for force was oriented normal to the crank arm, we could calculate the torques. Table II presents the results, showing that 60 in.-lbs. of torque would be the maximum required. From these results and assumptions, we chose a LEESON DC SUB-FHP Right-Angle Gearmotor, Catalog No. 1135045 (The catalog from Leeson Electric Corp., 1994), with a speed rage of 4.0 to 250 rpm, 52 in.-lbs. maximum torque, 1/4 input horse power, and 90 Volts DC maximum. We performed the experiments reported in Table II without bearings on the shafts, so we assume the actual torque required would be less than 60 in.-lbs. In addition, the experiment was performed for the most demanding silverware loads, namely a vertically-set conveyor with a full load of knives, the heaviest of silverware. This represents an extreme unlikely to occur in practice. Accordingly we assumed 52 in.-lbs. of torque would be sufficient for normal operations. The maximum motor speed of 250 rpm, delivering 160 ft./min. conveyor speed, is a compromise reduction from our desired maximums, but provides approximately 33% more speed than our nominal value of 120 ft./min. To adjust motor speed, we selected a KB ELECTRONICS Multi-Drive™ Solid State Variable Speed DC Motor Control KBMD-240D. (The instructions from KB Electronics, Inc., 1991)

Remaining details of the design for the magnetic lift conveyor are given in Appendix A. Results from operating the conveyor in conjunction with a batch silverware feeder are presented in Chapter V. In Chapter IV, we discuss the design of the feeder.

TABLE II

EXPERIMENTAL RESULTS
FORCE AND TORQUE REQUIRED TO TURN 4 IN. DIAMETER-CRANK FOR VARIOUS LOADS

Load (number of butter knives)	Force (lbs.)	Torque (in.-lbs.)
0	3	12
3	5	20
6	7	28
9	9	36
12	12	48
15	13	52
18	15	60

CHAPTER IV

FEEDER DESIGN

Hopper Design

In Chapter II, we described briefly the results with magnetic lift conveying that suggested a batch silverware feeding mechanism was needed. Moreover, those results suggested that a vibrating feeder with a metering mechanism at its discharge might be favorably combined with the magnetic lift conveyor. The concept, therefore, is to prevent silverware jamming by suitably vibrating batched silverware in a feeder, or hopper, which aligns each silverware piece in a direction perpendicular to conveyor motion as it exits the feeder. Moreover, the feeder exit, perhaps located sufficiently close to the HDPE conveyor cover, should meter individual pieces onto the conveyor. In what follows, we present a description of only the key elements in the design of the feeder. Appendix A presents details of the design, and discussion of details deemed unimportant for the principal purposes of this study is omitted.

The basic geometry of the vibrating feeder, or hopper, was selected as two vertical parallel side plates joined to oppositely inclined front and back plates, such that the top, or loading end of the hopper had approximately a square opening, suitable for dumping in a batch of mixed silverware. The bottom, or discharge end of the hopper would have a long narrow slot, oriented perpendicular to the direction of conveyor motion. The angles of these inclined plates and their elevations relative to the side plates were to be adjustable to provide needed flexibility during experiments. This design would permit studying the effects of various exit slot widths and heights above the conveyor, as well as effects of various slopes inside the hopper. The shape of the hopper discharge allows silverware pieces to leave in a lateral orientation and be attracted by two conveyor magnets in the same row. This would permit a silverware piece to be conveyed securely to the conveyor discharge. The distance between the hopper discharge and the conveyor should be sufficiently short to prevent silverware pieces from changing orientation. The details of the hopper design are presented in Appendix A. As discussed in Chapter I, the hopper volume was designed to hold 280 pieces of silverware.

In order to vibrate the hopper, we elected to mount it with vibration mounts on a suitable stationary frame. Vibration would be excited by mounting on the hopper a variable-speed electric motor with an unbalanced eccentric rotating shaft load. Varying the speed of the motor-vibrator and the amount of the eccentric unbalance would provide experimental flexibility in determining acceptable operating conditions. In what follows, we discuss the selection of the motor-vibrator and the vibration isolators.

Vibrator Selection

There are many electrically driven unbalanced-rotation vibrators available for industrial use, but the number of available small vibrators suitable for our application is limited. Anticipating that we would need no more than 500 lbs. of peak centrifugal force for our hopper full of silverware, we were able to locate only 3 commercially-available vibrators that delivered, respectively 100, 200, and 500 lbs. of centrifugal force. We planned to use a compact, low-weight vibrator that could deliver sufficient vibration amplitude to silverware in the hopper to prevent jamming. From the catalog from Hindon Corp. (1994), the following relationship can be used to obtain the amplitude of vibration of the hopper, assuming one degree of freedom motion:

$$A = \frac{CF}{14.2 \times \left(\frac{CPM}{1000}\right)^2 \times LOAD} \qquad (4.1)$$

where

A = Peak to Peak Amplitude (inches)

CF = Total Vibrating Centrifugal Force (pounds)

CPM = Frequency of Vibration (cycles per minute)

LOAD = Total "Sprung Load" of vibrating hopper, vibrator, and silverware load (pounds)

We assume a silverware load of 140 pieces weighing 12 lbs., and a hopper weight of 10 lbs., based upon crude calculations from the hopper design in Appendix A. From the catalog from Vibco, Inc. (1994), the weight of a 100 lbs. CF vibrator is 4 lbs., a 200lbs. CF vibrator is 12 lbs., and a 500 lbs. CF vibrator is 41 lbs. For various loads and vibrator speeds, Equation (4.1) can be used to calculate vibration amplitudes, and results are given in Table III.

Of course, the largest amplitude occurs for the 500 lbs. CF vibrator, but this vibrator is much larger than the other two. As a trade-off, we selected the 200 lbs. CF vibrator, namely a VIBCO SCR-200, with adjustable speed from 900 to 4000 rpm and adjustable centrifugal force to a maximum of 200 lbs. (The catalog from Vibco, Inc., 1994). Table III indicates that this would provide approximately 1/2 in. of peak to peak vibration amplitude at 950 RPM. If this amplitude proved insufficient to prevent silverware jamming, we planned to increase the centrifugal force at lower speeds by adding a heavier eccentric rotating weight. The vibrator was placed in the most convenient location, centered on top of hopper, as shown in Appendix A, fastened to

TABLE III

VIBRATION AMPLITUDE CALCULATION
EQUATION (4.1)

	Total Sprung Load (lbs.)		
	26	34	63
	Max. Vibrator Centrifugal Force (lbs.)		
Vibrator Speed (RPM)	100	200	500
	Max. Vibration Amplitude (in.)		
950	0.300	0.459	0.619
1150	0.205	0.313	0.423
4000	0.017	0.026	0.035

3/8 in. thick × 5 in. wide × 12-1/4 in. long plate spanning the hopper width. In this location, above the CG of the loaded hopper, it was expected that the hopper CG would undergo elliptical motion in a plane parallel with the hopper side plates. As such, Equation (4.1) does not strictly apply.

Isolator Selection

In order to mount the vibrating hopper to a fixed support structure and provide a degree of vibration isolation from this structure, suitable vibration mounts, or isolators, must be selected. Numerous suppliers of such mounts are available, with one of the largest being the Lord Corporation in Erie, PA (The catalog from Lord Corporation, 1993). Using the selector guide from the Lord Corporation catalog (1993), we first assume a reasonable desired isolation percentage I, such that the transmissibility T of the vibration to the structure becomes

$$T = 1 - \frac{I}{100} \tag{4.2}$$

Selecting I = 80% then yields T = 0.2. Next we estimate the lowest vibration frequency to be encountered, expecting this to be the worst condition. If high isolation is obtained at this frequency, we expect better isolation at higher frequencies, assuming that all such frequencies are above the natural frequencies of the structure. The lowest frequency available from the selected vibrator is 950 rpm, or 16 Hz. Next we determine the natural frequency, fn, that the isolated system needs to provide transmissibility T = 0.2 by employing: (The catalog from Lord Corporation, 1993)

$$T = \frac{1}{\left(\frac{fd}{fn}\right)^2 - 1} \tag{4.3}$$

where fd is the excitation or driving frequency in Hz and fn is the natural frequency of the vibrating structure in Hz. Substituting T = 0.2 and fd = 16 Hz yields fn = 7.2 Hz. Next, we determine the total vibrating load weight and divide by the number of equal vibration isolators supporting this weight to obtain the weight w per isolator. The total weight is the sum of 12 lbs. for silverware, 10 lbs. for the hopper, and 12 lbs. for the vibrator, equaling 34 lbs. We use 4 isolators on each side plate of the hopper for a total of 8, such that w = 34 / 8 ≈ 4 lbs. We then determine the required static deflection, ds, in inches, given by: (The catalog from Lord Corporation, 1993)

$$ds = \frac{9.8}{(fn)^2} \text{ (in.)},$$

where 9.8 is a constant with units $\text{in.-(cycle)}^2/(\text{sec})^2$ (4.4)

For fn = 7.2 Hz from above, the result from Equation (4.4) is ds = 0.189 in. Finally, we determine the required spring rate, K (lbs./in.), by employing: (The catalog from Lord Corporation, 1993)

$$K = \frac{w}{ds} \tag{4.5}$$

Using the previous values of w = 4 and ds = 0.189 yields K = 21 lbs./in.

The isolators should also support the dynamic load, so we should take the centrifugal force into account, yielding $w = (12 + 10 + 12 + 200) / 8 \approx 30$ lbs. Therefore, we should select the isolator which will handle a maximum load of 30 lbs, which would yield a spring rate, K, less than 21 lbs./in. We could not find a commercially-available isolator having such a small value for K and such a large load capacity. As a compromise, we selected a rubber shear mount from Lord (The catalog from Lord Corporation, 1993), Natural Rubber Medium Sandwich Mount Part No. J-3424-8, with a maximum static load of 33 lbs. and a spring rate in shear of 110 lbs./in. This spring rate is too large, which means vibration isolation will be much less than desired, and the support structure might vibrate, but we decided to solve such problems by clamping the system to a heavy table or by bolting to the floor. The isolation efficiency curve for flexible mounting systems and the load deflection curve for the medium sandwich mount 3424-8 for shear are given in Appendix D.

In the next section, Chapter V, we present results of silverware separation using the vibrating hopper described in this chapter and detailed in Appendix A, together with the magnetic lift conveyor described in Chapter III.

CHAPTER V

EXPERIMENTAL RESULTS

In order to evaluate silverware separation with our vibrating hopper-conveyor apparatus, we needed to measure at least three quantities: (1) the degree of separation of silverware pieces, one from another; (2) the degree of alignment of silverware pieces in a preferred direction, which we took to be perpendicular to the direction of conveyor motion; and (3) the rate of silverware piece discharge from the apparatus. Before detailed measurements of these quantities were made, it was necessary to fine-tune the operations of both the conveyor and the feeder to work out problems and find conditions most likely to be favorable for good silverware separation.

Fine Tuning the Conveyor

In early trials, we inclined the conveyor surface upward at 25° above horizontal and used 5 in. spacing between the aluminum strips, each carrying two magnets. However, we quickly learned that at this angle, the conveyor could not effectively convey knives oriented perpendicular to conveyor motion, although knives could be conveyed handle upwards. This occurred because the knife length was 9 inches, significantly larger than the magnet strip spacing, and the handle was significantly heavier than the blade. If knives are oriented in a direction parallel with conveyor motion, and handle downward, it is difficult to convey them upward, because a following magnet attracts the trailing knife handle, pulling it backward. Two mechanisms could be used to solve this problem: (1) increase the space between the aluminum strips; and (2) decrease the angle of the conveyor, making it more nearly horizontal. Because we wanted to keep the production rate as high as possible, we elected to decrease the conveyor angle to 10° below horizontal, which was the smallest angle we could achieve with the design presented earlier. Decreasing the angle to -10° significantly improved performance, and we also learned that increasing aluminum strip spacing to 10 inches gave much better alignment and separation of silverware pieces without decreasing production rate.

Fine Tuning the Feeder

As we expected, the amplitude of motion of the vibrating hopper was insufficient to prevent jamming of silverware in the hopper even when we operated with maximum rotating unbalance at a resonance frequency, experimentally found to be 16.7 Hz with 66 pieces of silverware in the hopper. To increase vibration amplitude, we elected to increase the eccentric weight of the vibrator motor. This was accomplished by bolting a semicircular plate of solid lead, 1 in. thick with a radius of 1-1/2 in., slightly larger than the existing eccentric, to the existing semicircular eccentrics. This is shown in Figure 5.1. This increased the overall rotating unbalance by a factor of 3, which provided a similar factor increase in vibration amplitude. This increase provided much better ability to prevent jamming.

Our original hopper design contained a top feed plate of HDPE sheet forming an entrance slot of adjustable width with the forward sloped panel of the hopper. The bottom of the hopper also contained an adjustable-width exit slot. In early trials, we discovered that the widths of these two slots had a pronounced effect on both the production rate and the separation ability of the apparatus. Drawing from our previous experience with Hindered Vertical Dropping, described in Chapter II, we elected to add an interior plate of HDPE sheet, sloping in a direction opposite to that of the top feed plate, and forming an adjustable-width slot with the rearward sloping panel of the hopper. It was felt that this addition might add some hindering to and metering of the silverware as it flowed through

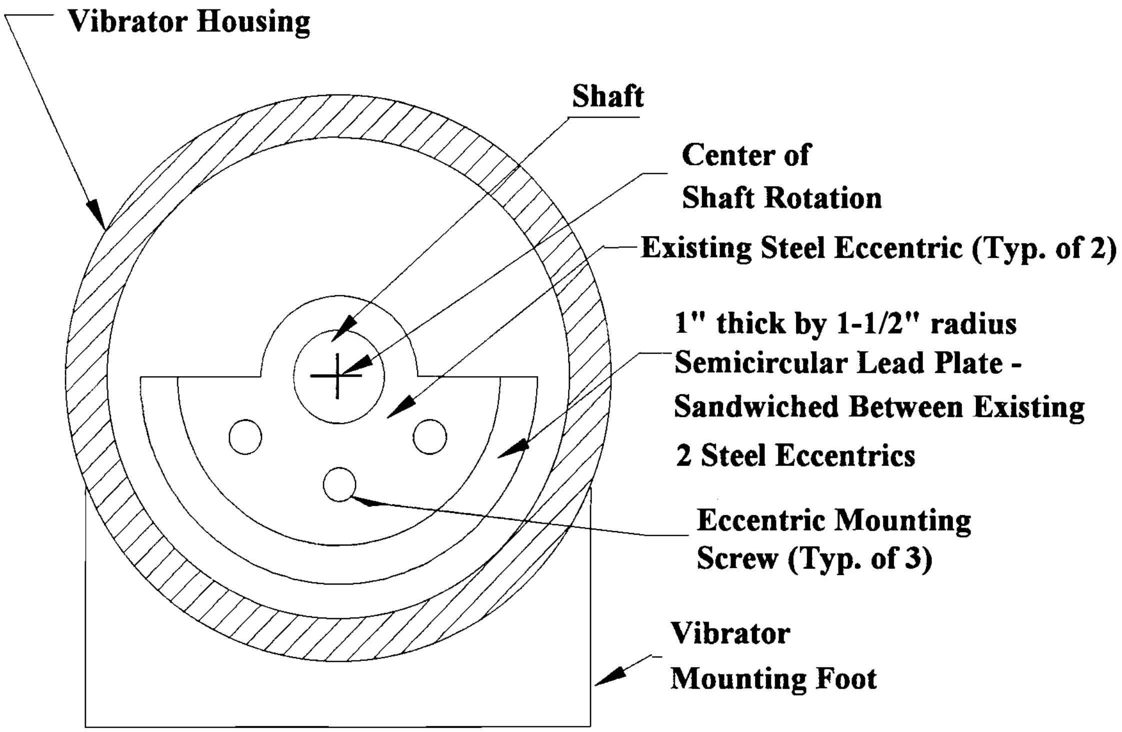


Figure 5.1 Eccentric on the Vibrator Motor

the vibrating hopper, thereby enhancing separation performance. Subsequent trials with this addition confirmed our belief, as reported in the results that follow. A schematic cross section of the hopper showing these panels and slot openings is shown in Figure 5.2.

Experimental Results

The purpose of this research is to investigate means to effectively separate silverware piece by piece. In order to measure separation, alignment, and production rate, we conducted an array of tests with two fixed batch sizes of silverware. A "large" batch consisted of 66 randomly mixed silverware pieces consisting of 15 butter knives, 21 dinner forks, 15 teaspoons, and 15 soup spoons. Silverware dimensions are given in Table I. Our "small" batch consisted of 33 randomly mixed silverware pieces consisting of 7 butter knives, 10 dinner forks, 8 teaspoons, and 8 soup spoons. The pieces of each type were identical to one another. In loading the "large" batch into the hopper for all experimental runs, we divided the batch into 3 equal-sized sub batches and dumped each sub batch into the hopper at five-second intervals. This was to provide for enhanced separation at the exit. For the "small" batch, we loaded the hopper by dumping in the entire batch at once.

To measure separation, for each test run on a silverware batch, we counted the number of silverware pieces that were separated on the magnetic conveyor from all other pieces. Dividing this number by the number of pieces in the batch (66 or 33) and multiplying by 100 gave the percent separated. Similarly, to determine alignment, for each test run on a silverware batch, we counted the number of silverware pieces on the magnetic conveyor that were aligned perpendicular to the direction of conveyor motion (parallel with the magnetic conveyor strips). Dividing by the batch pieces and multiplying by 100 gave the percent aligned. Finally, because the batch size was fixed at either 66 or 33 pieces, we could determine production rate by recording the length of time from when the first silverware piece was dumped into the hopper until the last piece was discharged from the conveyor. Thus, shorter run times for the same batch size indicated higher production rates.

Because of the random distribution and orientation of silverware pieces in each batch from run to run, and because of other possible variations in experimental conditions, we conducted each test at specified conditions three times and averaged the results over the three runs. Our experimental variables were conveyor speed, vibration frequency (which yielded various vibration displacement patterns), slot opening widths in the top and intermediate hopper panels, and silverware batch size. Because of the infinite number of possible combinations among these variables, we judiciously chose a few combinations which we believed would yield a sufficiently large range of results. The maximum conveyor speed was 158.1 ft./min., so we selected this value plus two lower values of 111.4 and 64.7 ft./min., such that the lowest speed was less than half the maximum speed. By trial and error, we discovered that resonance of thefully loaded hopper occurred at a

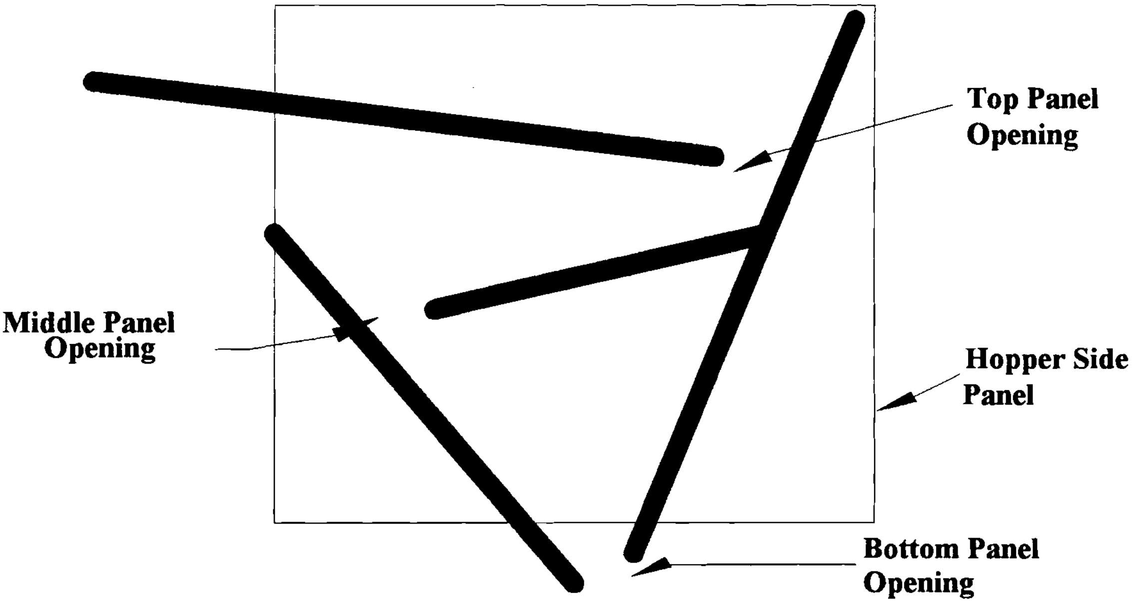
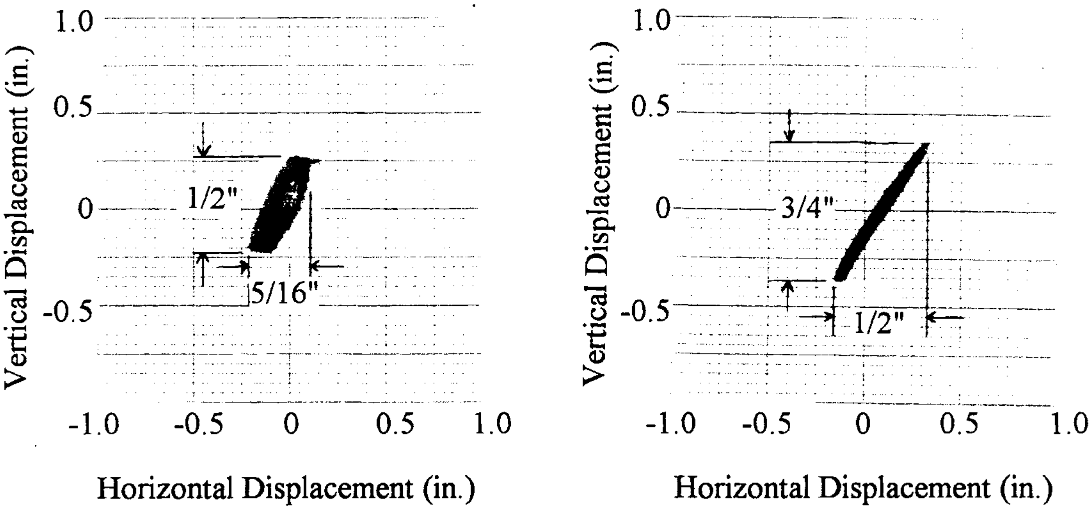


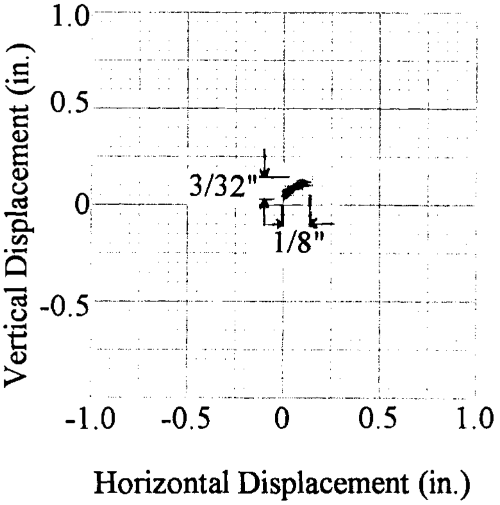
Figure 5.2 Cross Section of Hopper

driving frequency of 21.7 Hz, so we selected this value for maximum vibration amplitude, plus two other nearby frequencies of 16.7 Hz and 33.3 Hz, above and below the resonant frequency. Because we wanted to record the displacement pattern of vibration at these three frequencies, we mounted a stationary marking pen adjacent to the vibrating hopper with its point aligned in a side view of the hopper with the center of the hopper discharge slot. On the vibrating hopper side plate, we then affixed a small piece of graph paper centered on the aforementioned point. With the hopper vibrating, we then touched the marking pen to the graph paper, thus recording on "x-y trace" of the vibration displacement pattern on the graph paper. Since the hopper vibration is in a plane parallel with the hopper side plates, this pattern represents the motion of the center of the hopper discharge slot. These patterns are shown in Figure 5.3. Note that the largest excursions occur at the resonance frequency of 21.7 Hz. Also note that the shape of the vibration pattern, as well as their sizes, change with frequency. The maximum displacement strokes in the horizontal and vertical directions are indicated on each trace. We observe that



Displacement Pattern
for 16.7 Hz Frequency

Displacement Pattern
for 21.7 Hz Frequency



Displacement Pattern
for 33.3 Hz Frequency

Figure 5.3 Vibration Displacement Patterns of Feeder Discharge because the vibrator motor center of rotation is not located at the C.G. of the hopper-vibrator system, the vibration displacement pattern will vary from point to point in a plane parallel with the hopper side plate. In general, these patterns will be elliptical or linear (Hoberock, 1982), which is verified by the results in Figure 5.3.

The matrix of test conditions selected for the various test runs are given in Tables IV through VII. For the first set of experiments, we used the following feeder slot openings: 7/8 in. for the top slot, 3/4 in. for the middle slot, and 3/4 in. for the bottom slot, using the "large" silverware batch. The results are shown in Table IV. Next, we widened the slot openings as follows: 1-5/8 in. for the top slot and 1-1/2 in. for the middle slot. The bottom slot opening was kept at 3/4 in. as in the first set of experiments, and again we used the "large" silverware batch. The results of this second set of tests are shown in Table V. We then chose experimental conditions from both sets of experiments at gave the best separation results, namely 158.1 ft./min. for the conveyor motor speed and 21.7 Hz for the feeder vibration frequency. For this third set of experiments, we used the "small" silverware batch for the two different sets of slot openings in the first two sets of experiments. Our purpose was to investigate the effect of load size. In the final set of experiments, we again selected the "best" operating conditions, as above, but we removed the middle hopper panel completely and used the "large" silverware batch, with the other hopper slot openings set as in the first set of experiments. The purpose of this test was to determine the effect of multiple panels and slots in the hopper. Results are presented in Table VII.

Observation of separator performance during all of the experiments reported here indicated that no type of silverware piece was processed less effectively than any other type. Misalignment and failure to separate did not occur more for one type than for any other. We note from the results in Tables IV through VII that each of the experimental variables appeared to have some effect on the results. In some of the data, we note significant variation in the results among 3 runs under the some conditions, which is to be expected given the varying orientations and locations of silverware pieces in batches from test to test.

For the narrow slot opening runs in Table IV, the best average separation of 40.3%, although disappointingly low, occurred at the highest conveyor speed of 158.1 ft./min. and at the hopper resonance frequency of 21.7 Hz. Moreover, by comparison with results from the other Table IV - VII, 40.3 % separation was the highest achieved under any operating conditions. By contrast, the best average alignment of 14.9 % , again disappointingly low, occurred for the run with high conveyor speed / high frequency and for the run with middle conveyor speed / low frequency. Finally, the highest production rate, or lowest run times, in Table IV occurred at the highest frequency, and did not significantly vary with conveyor speed. We note that for a silverware batch of 66 pieces, a run time of 27 seconds yields a production rate of 147 pieces/min. We conclude from the results in Table IV that no single operating condition produced best results for all three outcomes of interest. We assume that good alignment is of the smallest interest because we might easily align silverware with a passive device downstream from the conveyor. If we also assume that separation is of the highest interest, we must ask whether the production rate at the highest separation percentage is acceptable. From Table IV, the average run time corresponding to the average 40.3 % separation was 41 seconds, which gives a production rate of 106 pieces per minute. This rate would handle in 26 minutes, all the silverware from a single meal in a 700-bed hospital with 4 silverware pieces per bed-meal, which seems quite acceptable.

In reviewing the results of the wide slot opening tests in Table V, we observe, in general, that separation and alignment percentages are lower than for comparable run conditions in Table IV. On the other hand, production rates are generally higher (run times are lower) in Table V than for comparable operating conditions in Table IV. We conclude that the narrower slot openings in the hopper panels are more desirable. We note that the slot openings used in Table IV were found by trial and error to be the lowest achievable without causing significant jamming of silverware in the hopper.

The results in Table VI support the conclusion drawn above that narrower slot openings in the hopper panels are preferable. Note, however, that for the small batch of silverware (half the size of the large batch used in Tables IV and V), the best average separation of 20.9 % is only half the best of 41 % for the large batch in Table IV. Moreover, the alignment percentage is also reduced by half from Table IV, while the production rate is approximately the same at 94 pieces/min. (half the silverware load processed in half the run time, compared with best results in Table IV). We conclude that batch size has a significant effect on separation size. However, the large batches in Tables IV and V were fed into the hopper in 3 equal sub-batches of 22 pieces at 5-second intervals, while the small batch of 33 pieces was fed into the hopper as a single batch. Observations during "large"-batch tests were that in most runs, all but a small number of pieces of a preceding sub-batch had cleared most of the hopper before a subsequent sub-batch was fed in 5 seconds after the start of the preceding sub batch. We conclude that feeding in a batch of 33 pieces as one batch is inferior to feeding in over intervals smaller sub-batches of 22 pieces.

Finally, in Table VII, we present results from operating with a large batch with the center hopper panel removed altogether. The results show that the alignment percentage and the production rate are reduced from those in Table V, which used a wide slot opening in the center hopper panel. However, the average separation of 20.9 % is approximately the same as the best of 23.9 % in Table V. Observation of separator performance during this experiment, however, indicated that up to 6 pieces of silverware were sometimes attached to one aluminum magnet-carrying strip, while with the center panel in place, maxima of only 3 pieces were so attached. We conclude that more interior panels yields better overall performance.

The photograph in Figure 5.4 shows the best result.

TABLE IV

EXPERIMENTAL RESULTS WITH NARROW SLOT OPENING

(Top Slot Opening: 7/8 in., Middle Slot Opening: 3/4 in., Bottom Slot Opening: 3/4 in.)
(Large Silverware Batch)

	Feeder Vibration Frequency		
	16.7 Hz	21.7 Hz	33.3 Hz
Separator Motor Speed (ft./min.)	% Silverware Separated / % Silverware Aligned / Run Time (Secs.)		
64.7	Test #(1) 13.4 / 7.5 / 38	(1) 25.4 / 6.0 / 42	(1) 1.5 / 1.5 / 22
	Test #(2) 10.4 / 6.0 / 31	(2) 23.9 / 6.0 / 39	(2) 11.9 / 3.0 / 25
	Test #(3) 29.9 / 17.9 / 57	(3) 23.9 / 7.5 / 37	(3) 3.0 / 1.5 / 24
	(Avg.) 17.9 / 10.4 / 42	(Avg.) 23.9 / 6.0 / 39	(Avg.) 6.0 / 1.5 / 24
111.4	Test #(1) 31.3 / 19.4 / 35	(1) 37.3 / 6.0 / 40	(1) 17.9 / 10.4 / 34
	Test #(2) 28.4 / 14.9 / 36	(2) 34.3 / 10.4 / 39	(2) 17.9 / 4.5 / 26
	Test #(3) 37.3 / 10.4 / 47	(3) 38.8 / 20.9 / 50	(3) 13.4 / 3.0 / 20
	(Avg.) 32.8 / 14.9 / 39	(Avg.) 37.3 / 11.9 / 43	(Avg.) 16.4 / 6.0 / 27
158.1	Test #(1) 32.8 / 6.0 / 35	(1) 34.3 / 6.0 / 37	(1) 28.4 / 7.5 / 28
	Test #(2) 29.9 / 6.0 / 44	(2) 53.7 / 20.9 / 55	(2) 31.3 / 19.4 / 24
	Test #(3) 34.3 / 3.0 / 56	(3) 32.8 / 11.9 / 30	(3) 32.8 / 19.4 / 29
	(Avg.) 32.8 / 4.5 / 45	(Avg.) 40.3 / 13.4 / 41	(Avg.) 31.3 / 14.9 / 27

TABLE V

EXPERIMENTAL RESULTS
WITH WIDE SLOT OPENING

(Top Slot Opening: 1-5/8 in., Middle Slot Opening: 1-1/2 in.,
Bottom Slot Opening: 3/4 in.)
(Large Silverware Batch)

	Feeder Vibration Frequency		
	16.7 Hz	21.7 Hz	33.3 Hz
Separator Motor Speed (ft./min.)	% Silverware Separated / % Silverware Aligned / Run Time (Secs.)		
64.7	Test #(1) 7.5 / 1.5 / 30	(1) 6.0 / 6.0 / 20	(1) 4.5 / 1.5 / 20
	Test #(2) 4.5 / 0 / 27	(2) 6.0 / 1.5 / 23	(2) 3.0 / 3.0 / 19
	Test #(3) 4.5 / 3.0 / 24	(3) 4.5 / 1.5 / 23	(3) 3.0 / 1.5 / 22
	(Avg.) 6.0 / 1.5 / 27	(Avg.) 6.0 / 3.0 / 22	(Avg.) 3.0 / 1.5 / 20
111.4	Test #(1) 19.4 / 1.5 / 19	(1) 20.9 / 10.4 / 24	(1) 16.4 / 9.0 / 31
	Test #(2) 26.9 / 14.9 / 33	(2) 17.9 / 3.0 / 24	(2) 16.4 / 3.0 / 30
	Test #(3) 14.9 / 7.5 / 23	(3) 20.9 / 4.5 / 22	(3) 9.0 / 4.5 / 22
	(Avg.) 20.9 / 7.5 / 25	(Avg.) 19.4 / 6.0 / 23	(Avg.) 13.4 / 6.0 / 27
158.1	Test #(1) 20.9 / 6.0 / 19	(1) 19.4 / 6.0 / 22	(1) 13.4 / 10.4 / 22
	Test #(2) 23.9 / 1.5 / 24	(2) 23.9 / 3.0 / 57	(2) 11.9 / 4.5 / 22
	Test #(3) 19.4 / 6.0 / 24	(3) 28.4 / 7.5 / 42	(3) 19.4 / 9.0 / 20
	(Avg.) 20.9 / 4.5 / 22	(Avg.) 23.9 / 6.0 / 40	(Avg.) 14.9 / 7.5 / 21

TABLE VI

EXPERIMENTAL RESULTS
SLOT OPENING COMPARISON

(Separator Motor Speed: 158.1 ft./min.)
(Feeder Vibration Frequency: 21.7 Hz)
(Small Silverware Batch)

	Slot Opening (Top / Middle / Bottom)	
	7/8 in. / 3/4 in. / 3/4 in.	1-5/8 in. / 1-1/2 in. / 3/4 in.
	% Silverware Separated / % Silverware Aligned / Run Time (Secs.)	
Test #(1)	22.4 / 10.4 / 16	7.5 / 6.0 / 9
Test #(2)	26.9 / 6.0 / 24	4.5 / 0 / 11
Test #(3)	11.9 / 4.5 / 22	16.4 / 1.5 / 20
(Avg.)	20.9 / 7.5 / 21	9.0 / 3.0 / 13

TABLE VII

EXPERIMENTAL RESULTS
WITHOUT CENTER HOPPER PANEL

(Separator Motor Speed: 158.1 ft./min.)
(Feeder Vibration Frequency: 21.7 Hz)
(Top Slot Opening: 7/8 in., Bottom Slot Opening: 3/4 in.)
(Large Silverware Batch)

% Silverware Separated / % Silverware Aligned / Run Time (Sec.)

Test #(1) 16.4 / 1.5 / 30
Test #(2) 22.4 / 3.0 / 28
Test #(3) 25.4 / 6.0 / 24
(Avg.) 20.9 / 3.0 / 27

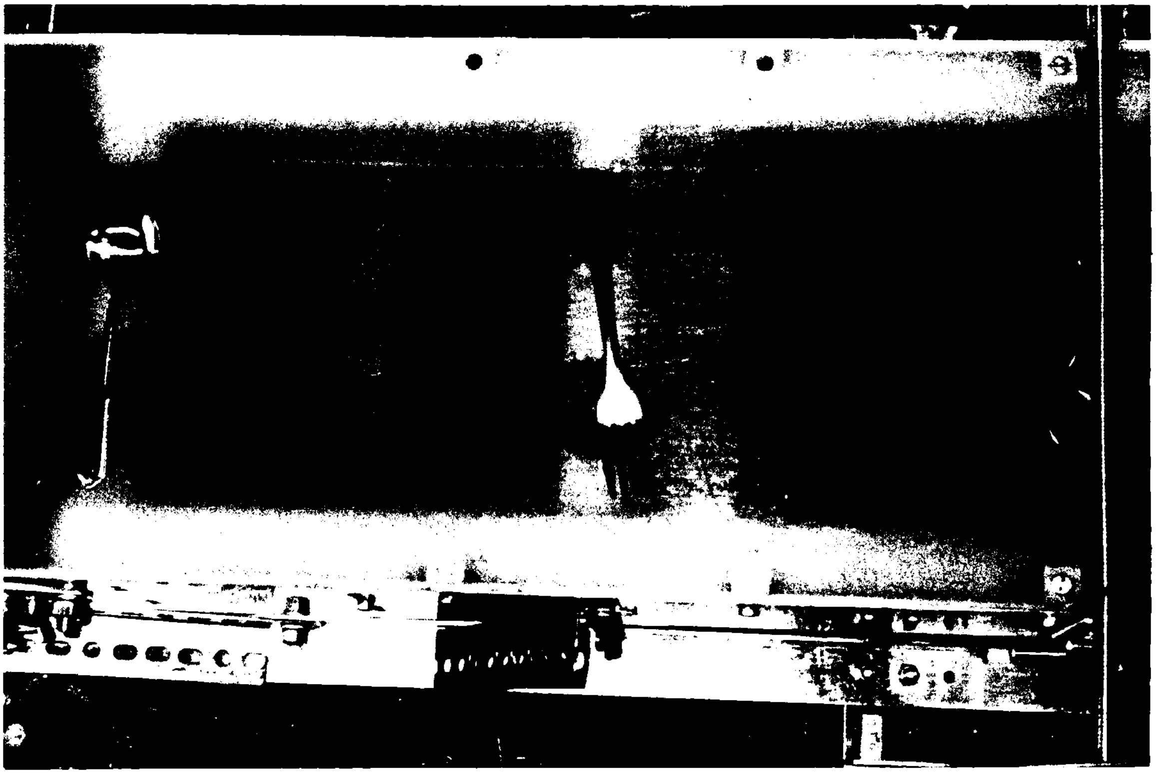


Figure 5.4 Best Result of Vibrating Hopper-Conveyor

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Basic Results

We have focused, in this research, on investigation of separation of silverware, to be ultimately used for machine vision sorting and inspection for commercial silverware washing applications. The major contributions of this research may be summarized as follows:

1. A prototype method for separating silverware has been identified and implemented.
2. A novel magnetic conveyor was designed, constructed, and evaluated. While this device appears to have merit, there is room for improvement to orient each silverware piece in a cross-conveyor direction.
3. A vibrating feed hopper was designed, constructed, and evaluated. It appears that this device has significant potential for reaching good separation performance, with suitable modification.
4. The feeder / conveyor combination can achieve good production rates of silverware. However, the best separation percentage of 41 % achieved with the current prototype is much too low for the apparatus to be commercially viable. However, adding additional interior hopper panels to solve this problem has high potential.
5. The best alignment percentage of 14.9 % achieved suggests that either alternate

alignment means should be added to the conveyor discharge, or additional magnets should be added to the aluminum magnet-carrying strips.

Future Research

We recommend that the hopper be re-designed, such that its overall height is several times that of the current prototype, with multiple interior panels. Results presented in Chapter V suggest that more "hold-up" or hindering inside the hopper will increase separation percentage. We also recommend that means be devised to automatically feed several batches, rather than large batches, of silverware into the hopper. Finally, passive alignment channels added to the conveyor discharge should be investigated as a means to solve the alignment problem. Additional magnets added to each magnet-carrying strip should also be studied.

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APPENDIXES

APPENDIX A

DETAILED DRAWING OF SEPARATOR AND FEEDER

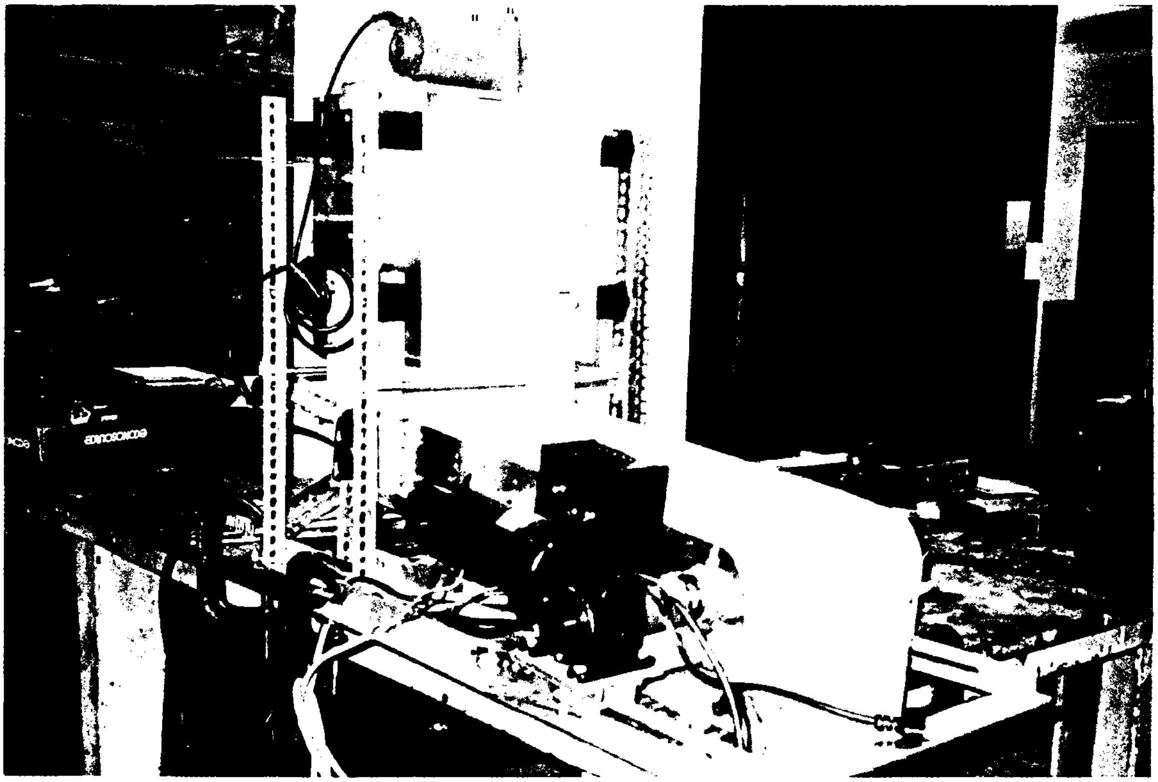


Figure A.1 Vibrating Hopper-Conveyor Apparatus

TABLE VIII

VIBRATING HOPPER-CONVEYOR PARTS

No.	Figure	Page	Part Name	No. Req.
1			VIBCO SCR-200	1
2	A.4	67	Vibrator Base	1
3	A.5	68	Hopper Side Plate	2
4			0.074" x 1-1/2" x 27" Galvanized Slotted Angle	4
5	A.6	69	Hopper Side Plastic Cover	2
6			1" dia. x 19" All Thread Steel Rod, 13 NC Coarse	2
7	A.7	70	Conveyor Side Plate	2
8	A.8	71	Conveyor Plastic Cover	1
9			KB ELECTRONICS Multi-Drive™ Solid State Variable Speed DC Motor Control KBMD-240D	1
10			LEESON DC SUB-FHP Right Angle Gearmotor, Catalog No. 1135045	1
11	A.9	72	Conveyor Motor Base	1
12	A.10	72	Vibrating Hopper-Conveyor Apparatus Base Plate (Forth)	1
13			0.074" x 1-1/2" x 2-1/4" Galvanized Slotted Angle	2
14	A.11	73	Conveyor Motor Base Angle	1
15			0.074" x 1-1/2" x 6-1/2" Galvanized Slotted Angle	2
16	A.12	73	Vibrating Hopper-Conveyor Apparatus Base Plate (Third)	1
17	A.13	73	Chain Adjuster	2
18	A.14	74	Vibrating Hopper-Conveyor Apparatus Base Plate (Second)	1

19			0.074" × 1-1/2" × 5-1/4" Galvanized Slotted Angle	2
20	A.15	74	Vibrating Hopper-Conveyor Apparatus Base Plate (First)	1
21	A.16	74	Hopper Base Angle	2
22			• 5/8" dia. × 14" long Steel Shaft • U.S. TSUBAKI SPROCKET 50B12F - No. 50 5/8" Pitch Finished Bore - 5/8" Bore Dia. • DAYTON Flange Mount Pillow Block - Light Duty Ball Bearing, Self-Aligning - 5/8" Bore Dia.	1 2 2
23			LORD Natural Rubber Medium Sandwich Mount Part No. J-3424-8	8
24	A.17	75	Back Hopper Sloping Panel	1
25	A.18	76	Center Sloping Hopper Panel	1
26			SOLIDUR TIVAR ANSI Standard Roller Chain Guide - Profile K No. 50 - 22" Ea.	4
27	A.19	76	Magnet-Carrying Aluminum Strip	6
28			U.S. TSUBAKI Standard Attachment Chain No. RS50-1 8L WA2, 96 Pitches	2
29			• 1" dia. × 15" long Steel Shaft • U.S. TSUBAKI SPROCKET 50B12F - No. 50 5/8" Pitch Finished Bore - 1" Bore Dia. • DAYTON Flange Mount Pillow Block - Light Duty Ball Bearing, Self-Aligning - 1" Bore Dia.	1 2 2
30	A.20	76	Conveyor Base Angle	2
31	A.21	77	Front Hopper Sloping Panel	1
32	A.22	78	Top Feed Hopper Panel	1

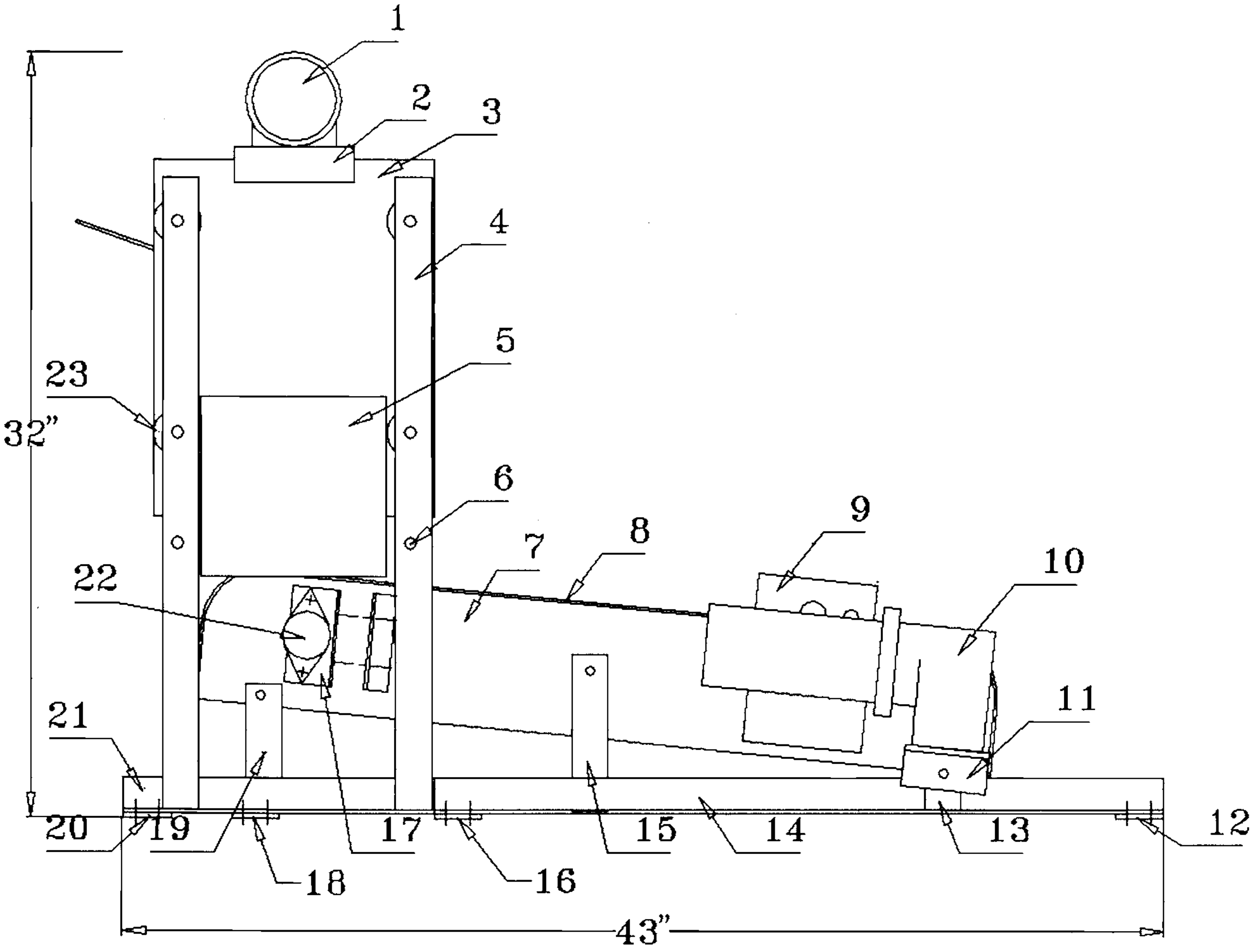


Figure A.2 Side View of Vibrating Hopper-Conveyor Apparatus (See TABLE VIII for Numbered Part Description)

Scale: 1" = 8"

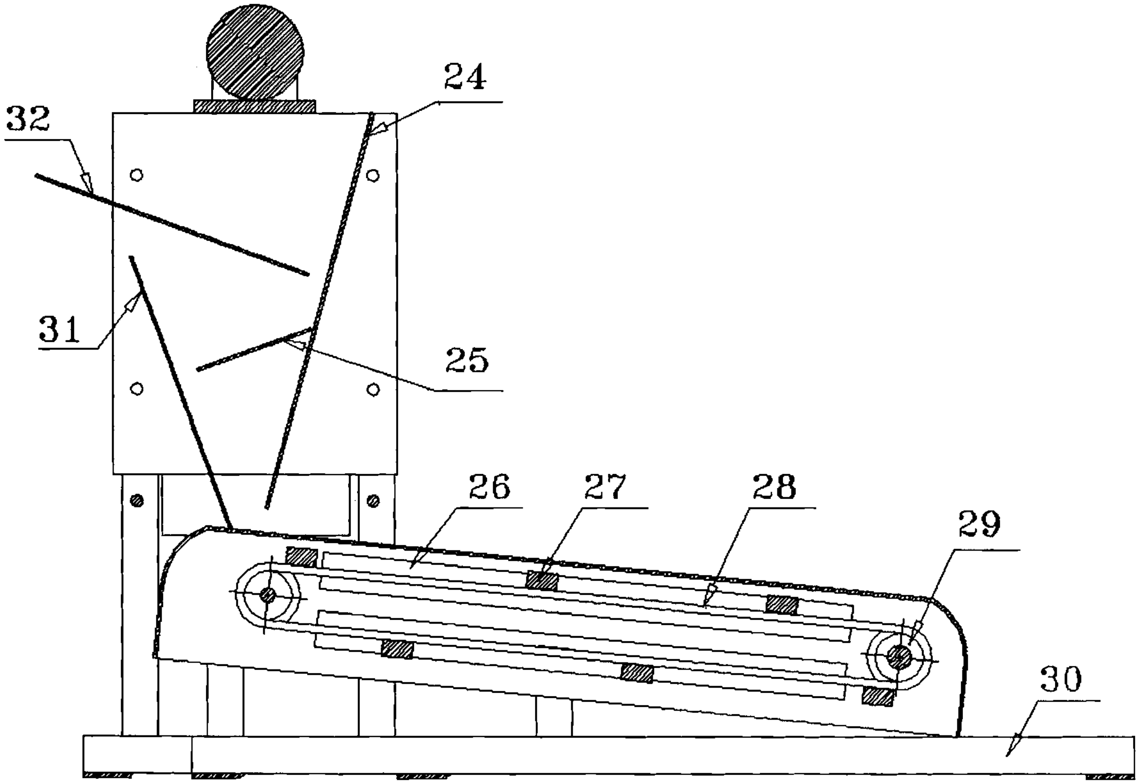


Figure A.3 Cross Sectional Side View of Vibrating Hopper-Conveyor Apparatus
(See TABLE VIII for Numbered Part Description)

Scale: 1" = 8"

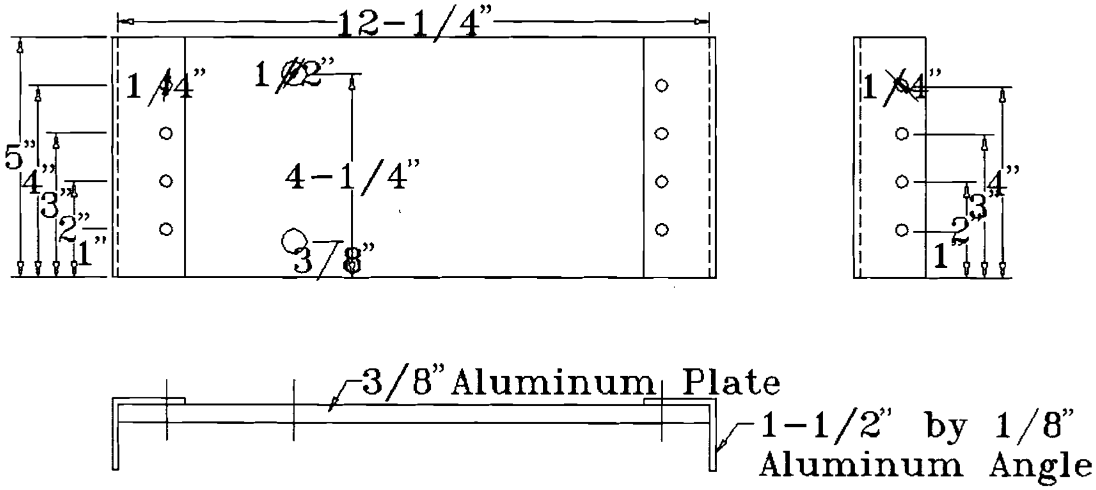


Figure A.4 Vibrator Base, Part #2 Scale: 1" = 4"
(See TABLE VIII)

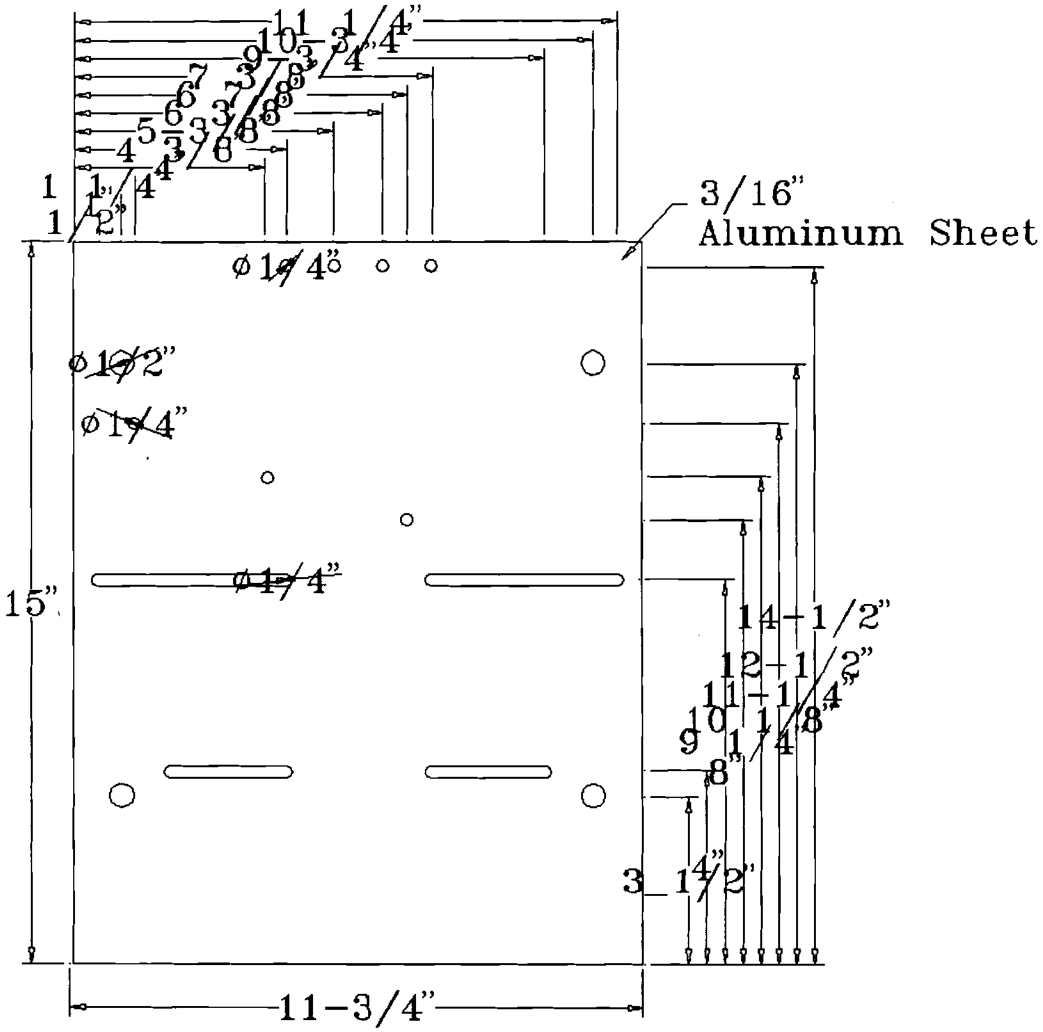


Figure A.5 Hopper Side Plate, Part #3
(See TABLE VIII)

Scale: 1" = 4"

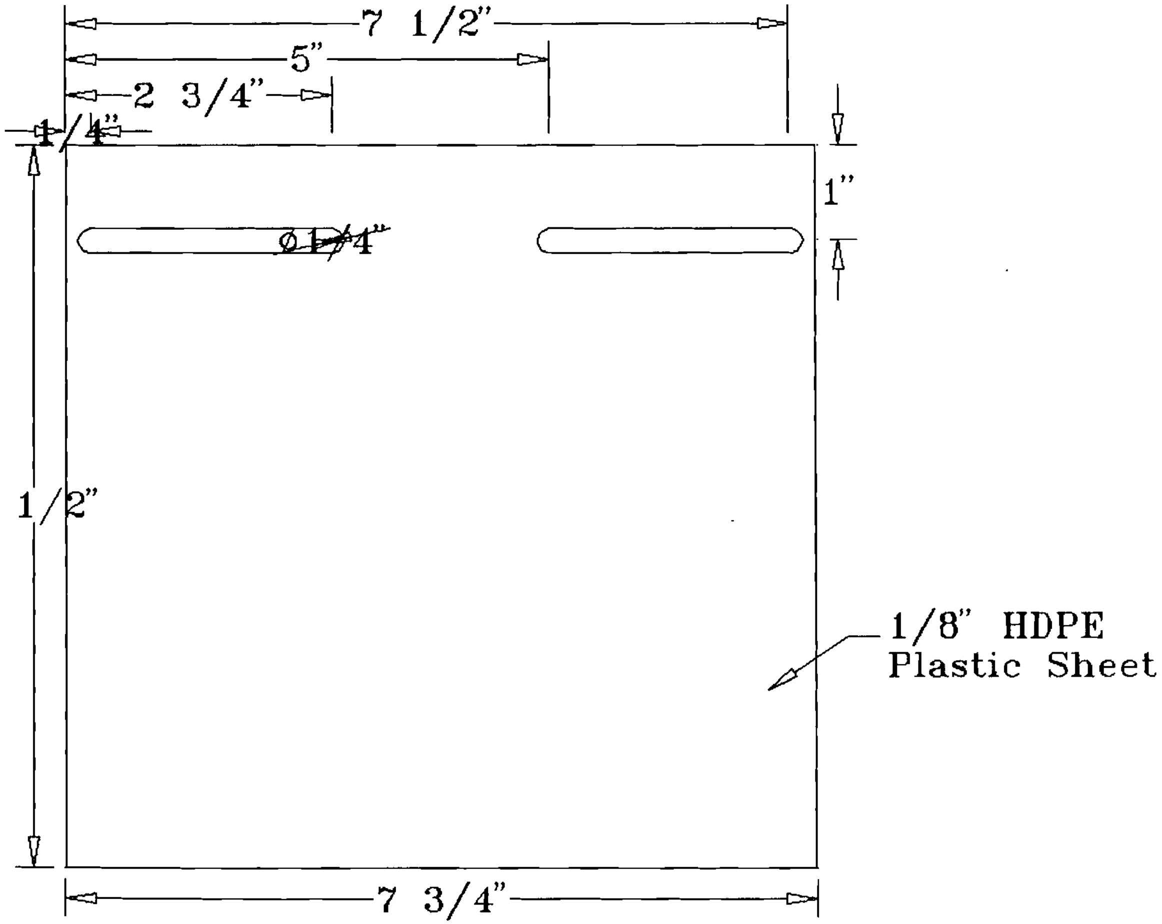
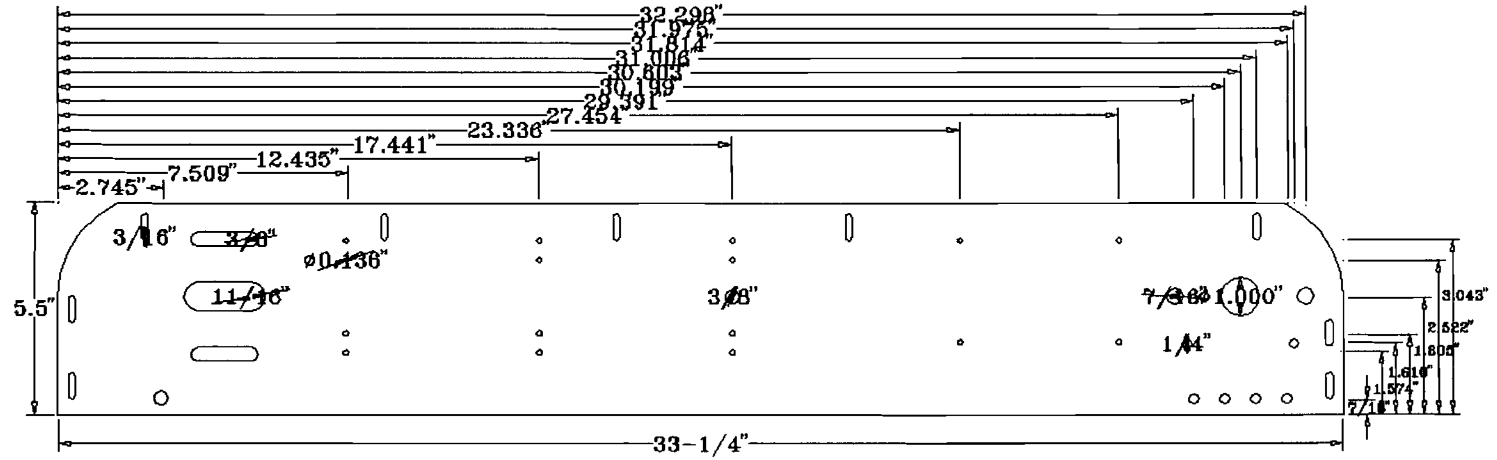


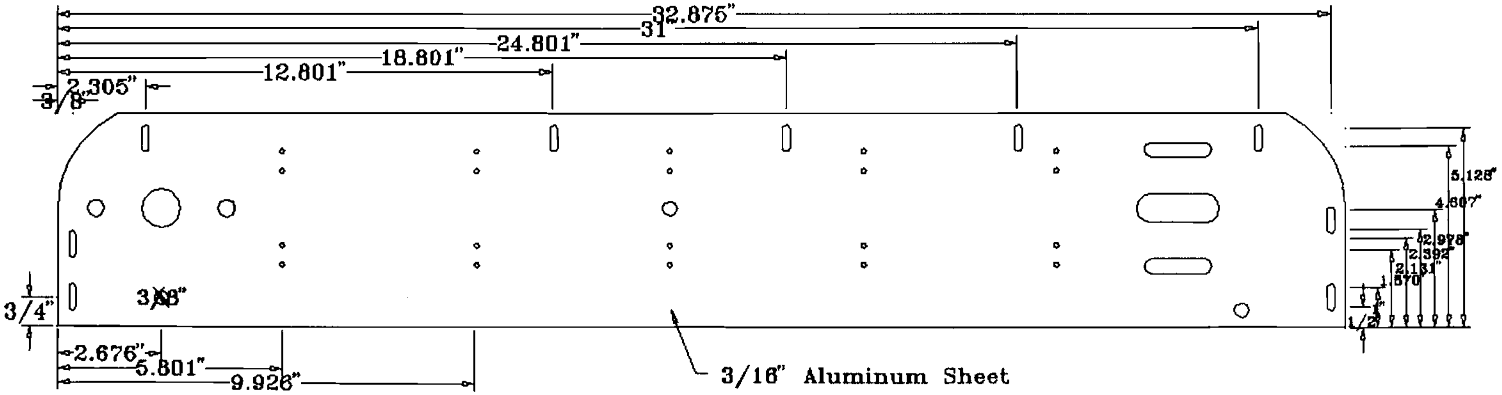
Figure A.6 Hopper Side Plastic Cover, Part #5
(See TABLE VIII)

Scale: 1" = 2"



Right Side Panel

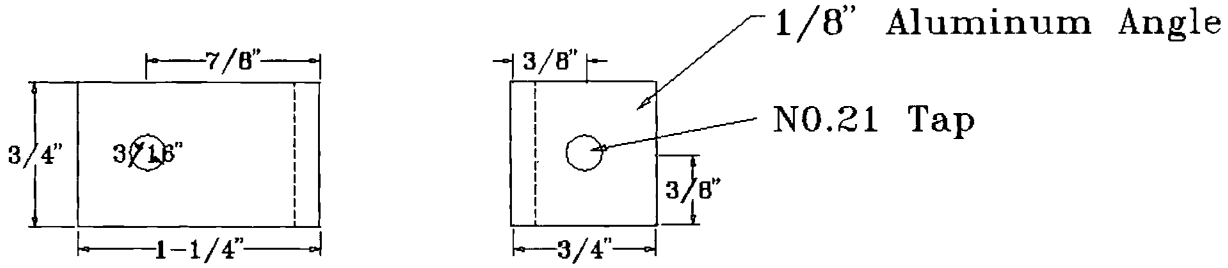
(All Component Dimensions Horizontally Reversed From Left Side Panel, but Vertically Identical)



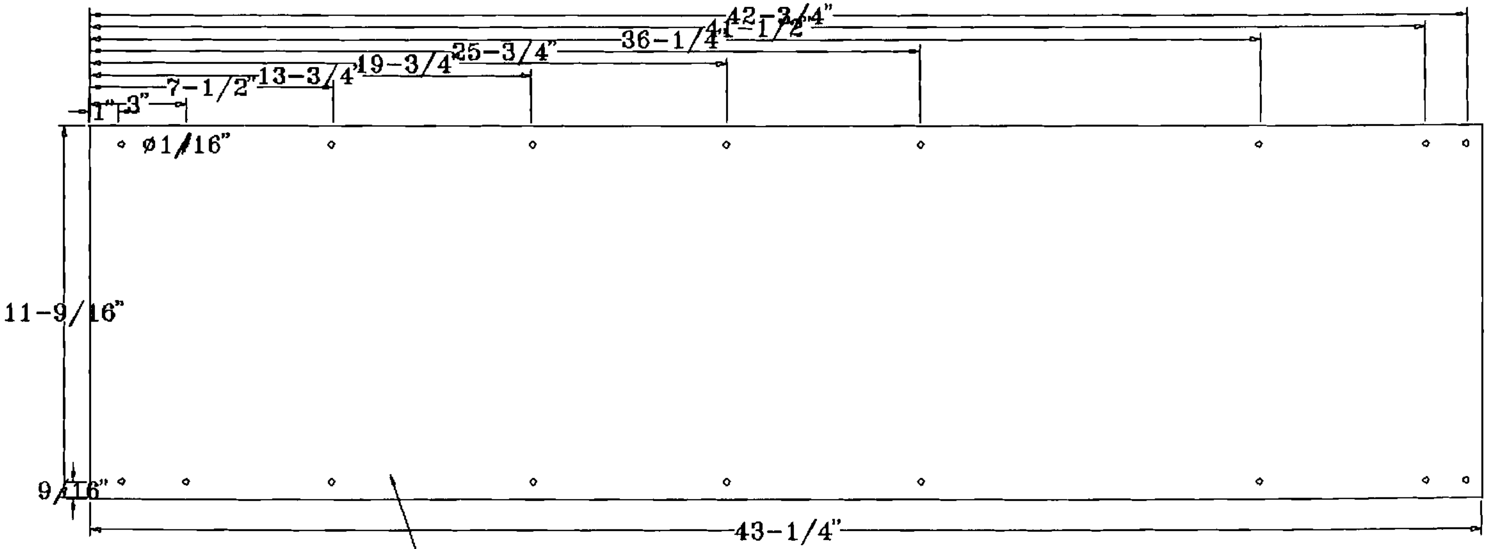
Left Side Panel

(All Component Dimensions Horizontally Reversed From Right Side Panel, but Vertically Identical)

Figure A.7 Conveyor Side Panel, Part #7 Scale: 1" = 5"
(See TABLE VIII)



Attachment Brackets (18 Pieces) Scale 1" = 1"



Scale 1" = 6 "

Figure A.8 Conveyor Plastic Cover, Part #8, with Attachment Brackets
(See TABLE VIII)

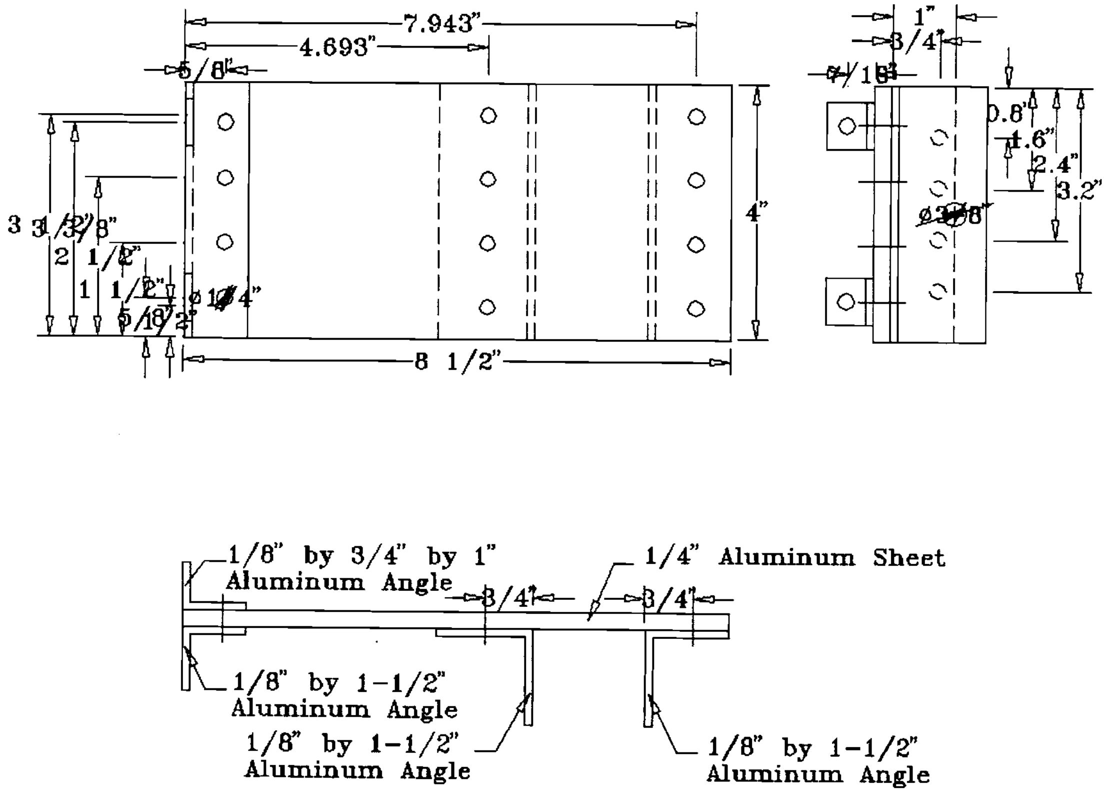


Figure A.9 Conveyor Motor Base, Part #11 Scale: 1" = 3"
(See TABLE VIII)

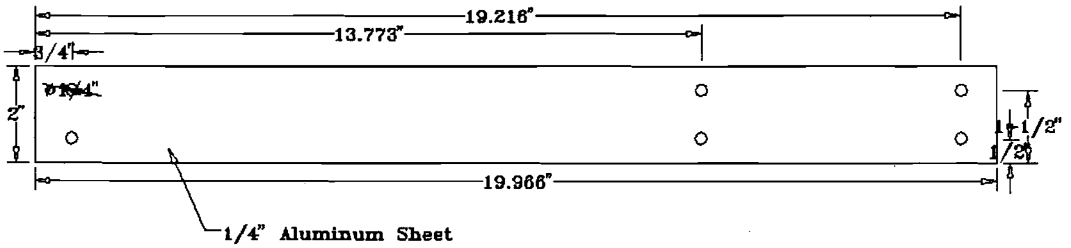


Figure A.10 Vibrating Hopper-Conveyor Apparatus Base Plate (Fourth), Part #12
Scale: 1" = 4" (See TABLE VIII)

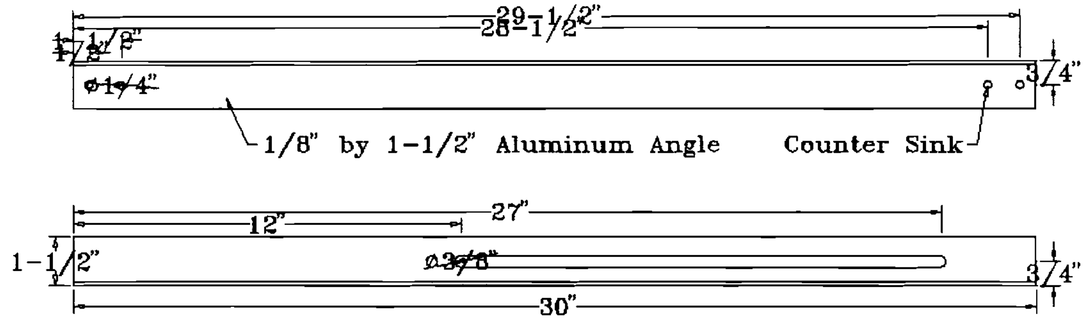


Figure A.11 Conveyor Motor Base Angle, Part #14 Scale: 1" = 6"
(See TABLE VIII)

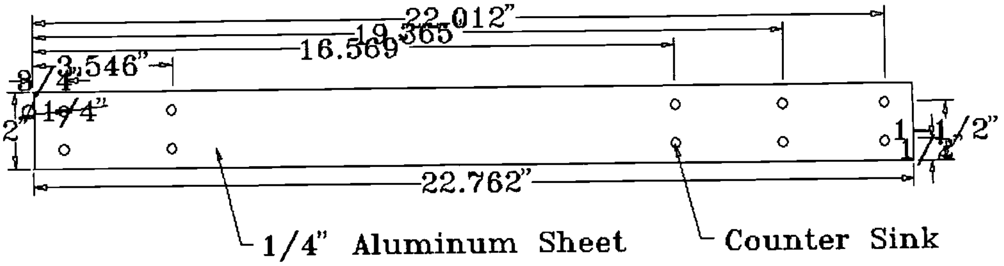


Figure A.12 Vibrating Hopper-Conveyor Apparatus Base Plate (Third), Part #16
Scale: 1" = 5" (See TABLE VIII)

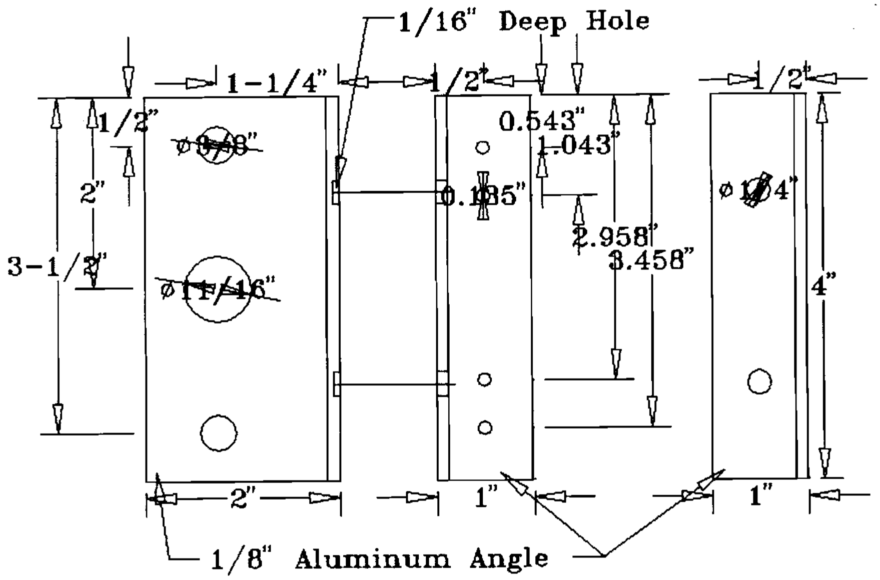


Figure A.13 Chain Adjuster, Part # 17 Scale: 1" = 2"
(See TABLE VIII)

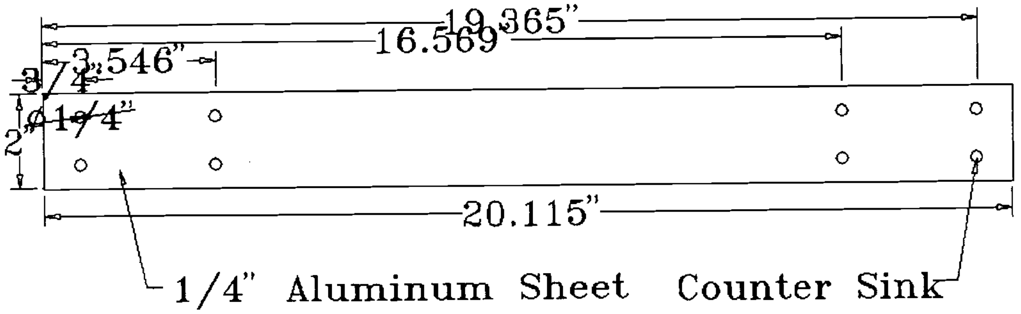


Figure A.14 Vibrating Hopper-Conveyor Apparatus Base Plate (Second), Part #18
Scale: 1" = 4" (See TABLE VIII)

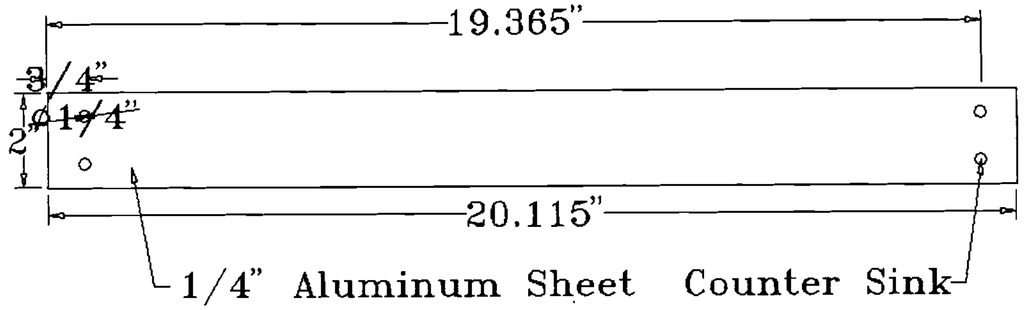


Figure A.15 Vibrating Hopper-Conveyor Apparatus Base Plate (First), Part #20
Scale: 1" = 4" (See TABLE VIII)

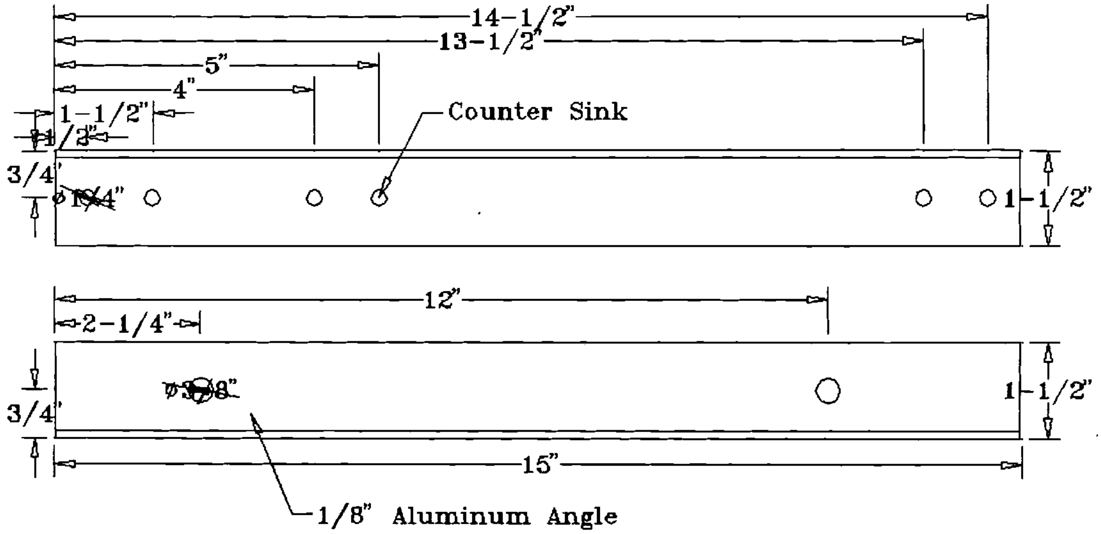


Figure A.16 Hopper Base Angle, Part #21 Scale: 1" = 3"
(See TABLE VIII)

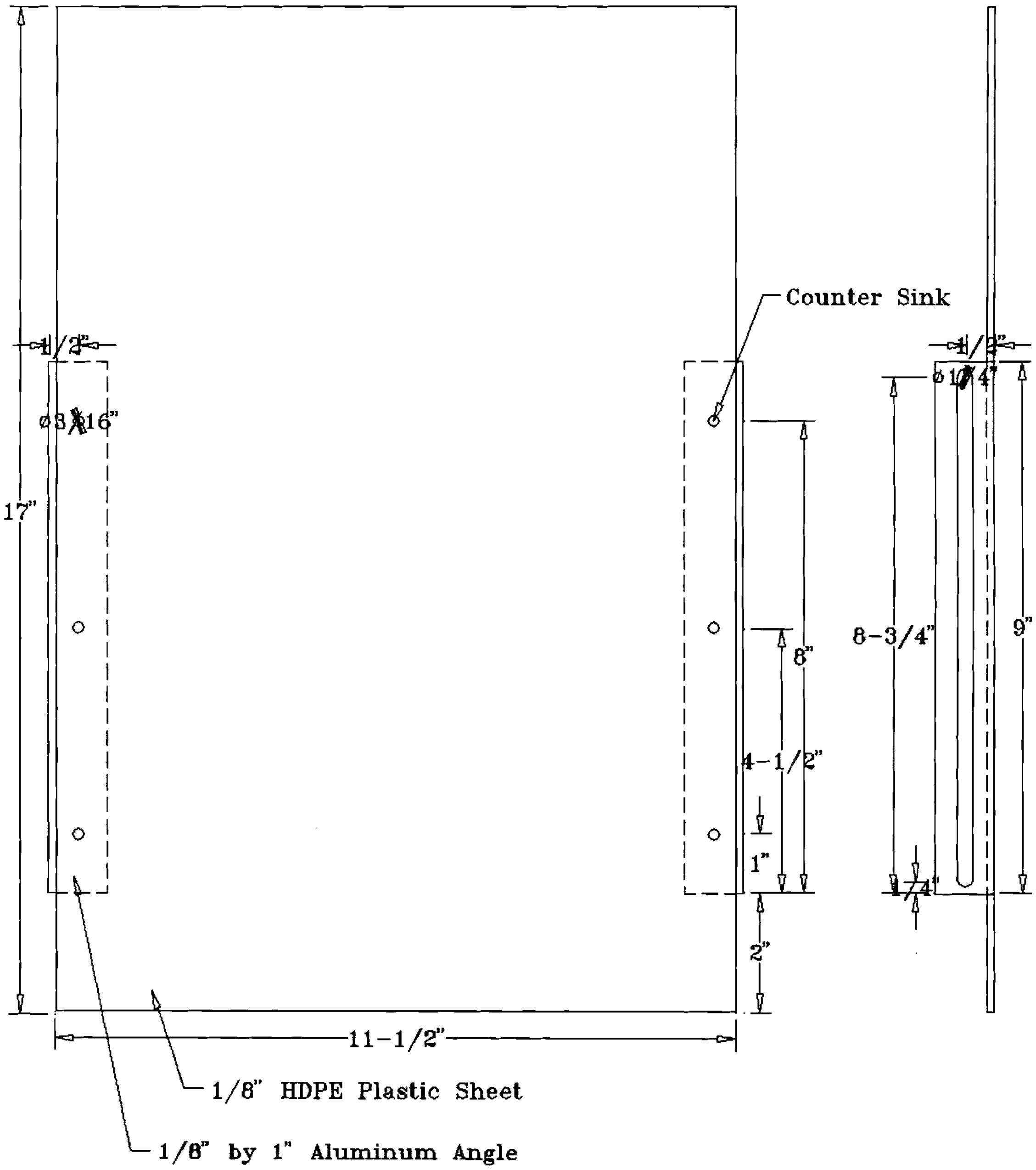


Figure A.17 Back Hopper Sloping Panel, Part #24
(See TABLE VIII)

Scale: 1" = 3"

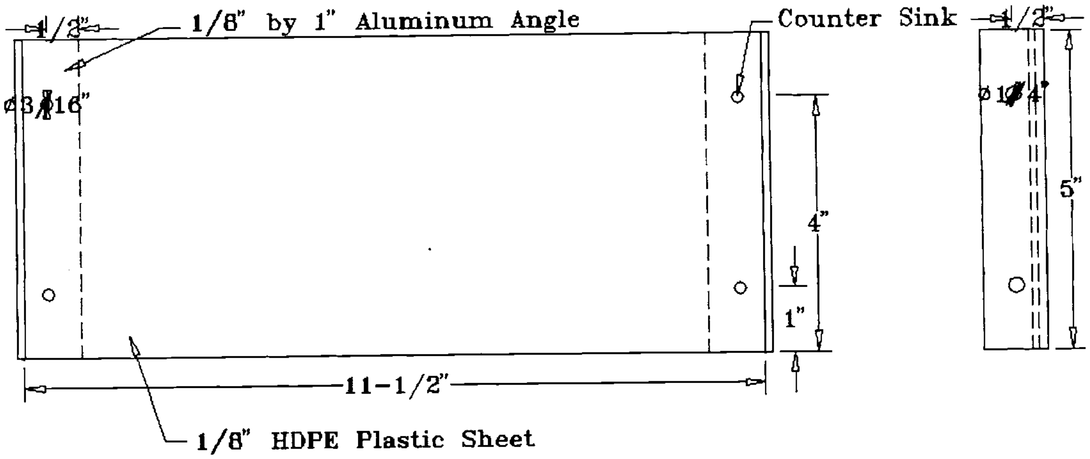


Figure A.18 Center Sloping Hopper Panel, Part #25 Scale: 1" = 3"
(See TABLE VIII)

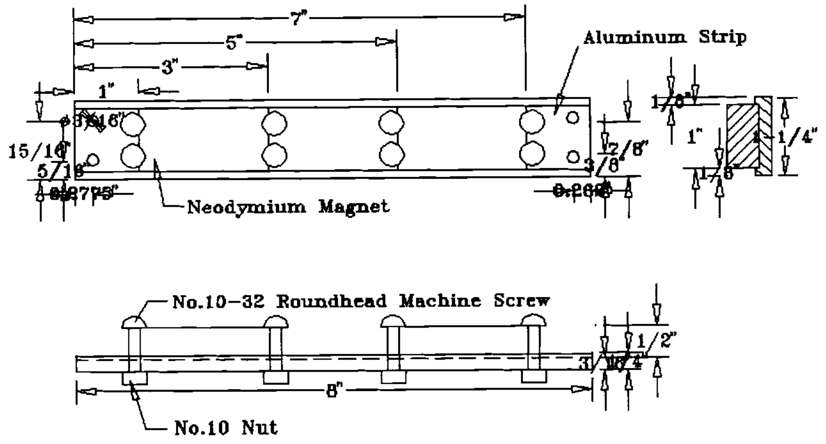


Figure A.19 Magnet-Carrying Aluminum Strip, Part #27 Scale: 1" = 3"
(See TABLE VIII)

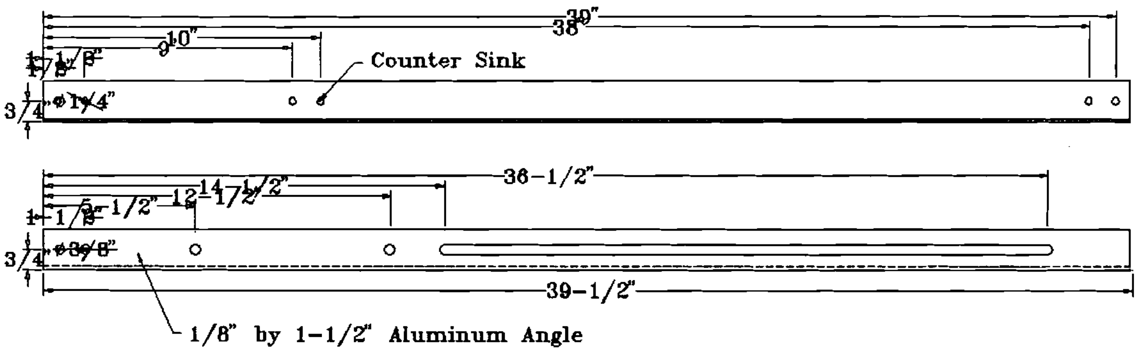


Figure A.20 Conveyor Base Angle, Part #30 Scale: 1" = 7"
(See TABLE VIII)

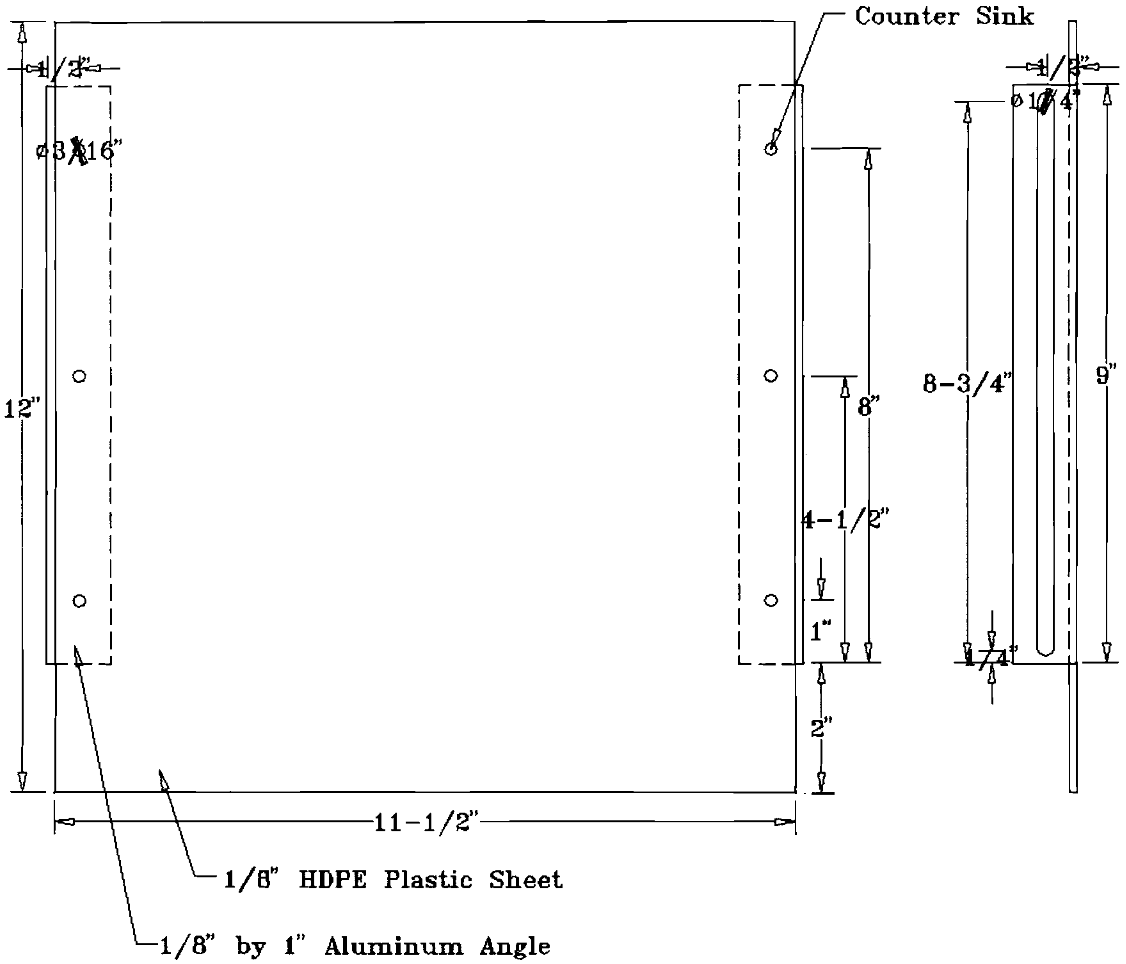


Figure A.21 Front Hopper Sloping Panel, Part #31 Scale: 1" = 3"
(See TABLE VIII)

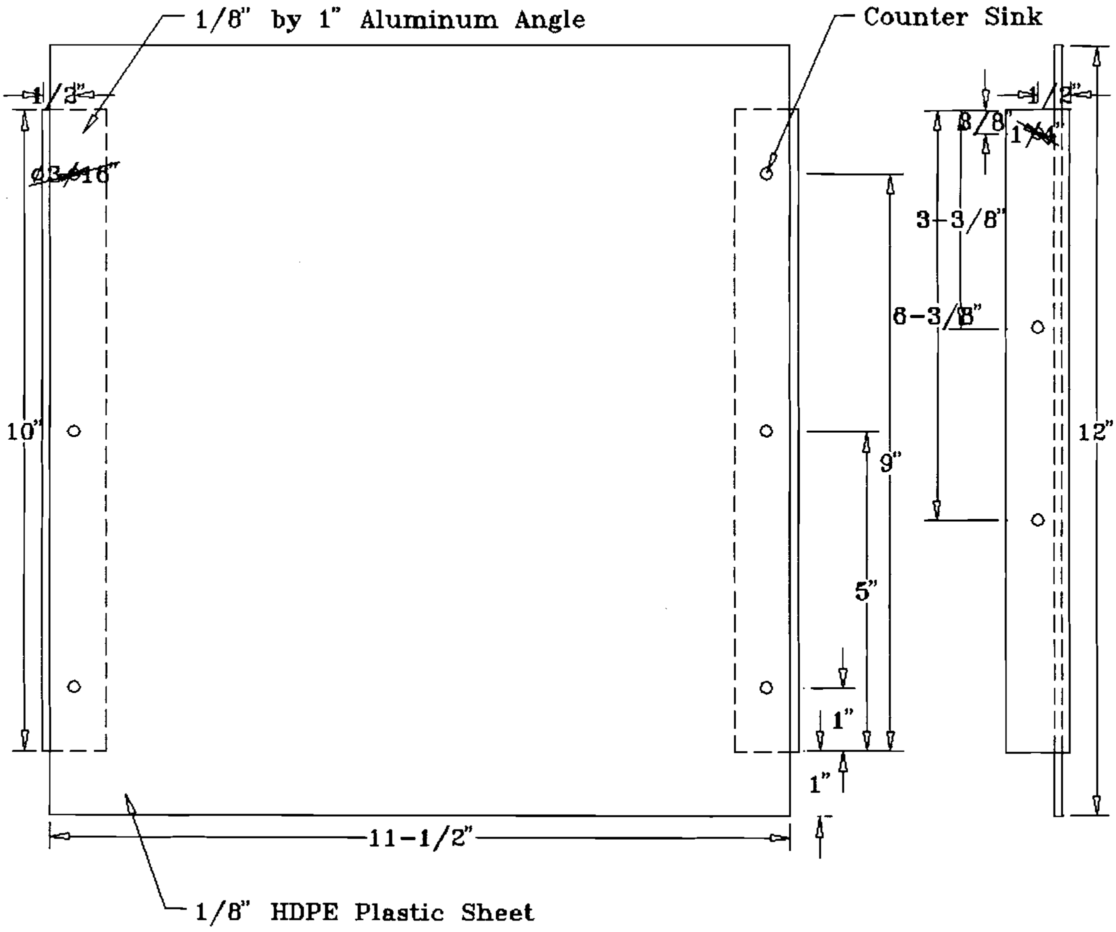


Figure A.22 Top Feed Hopper Plate, Part #32 (See TABLE VIII) Scale: 1" = 3"

APPENDIX B

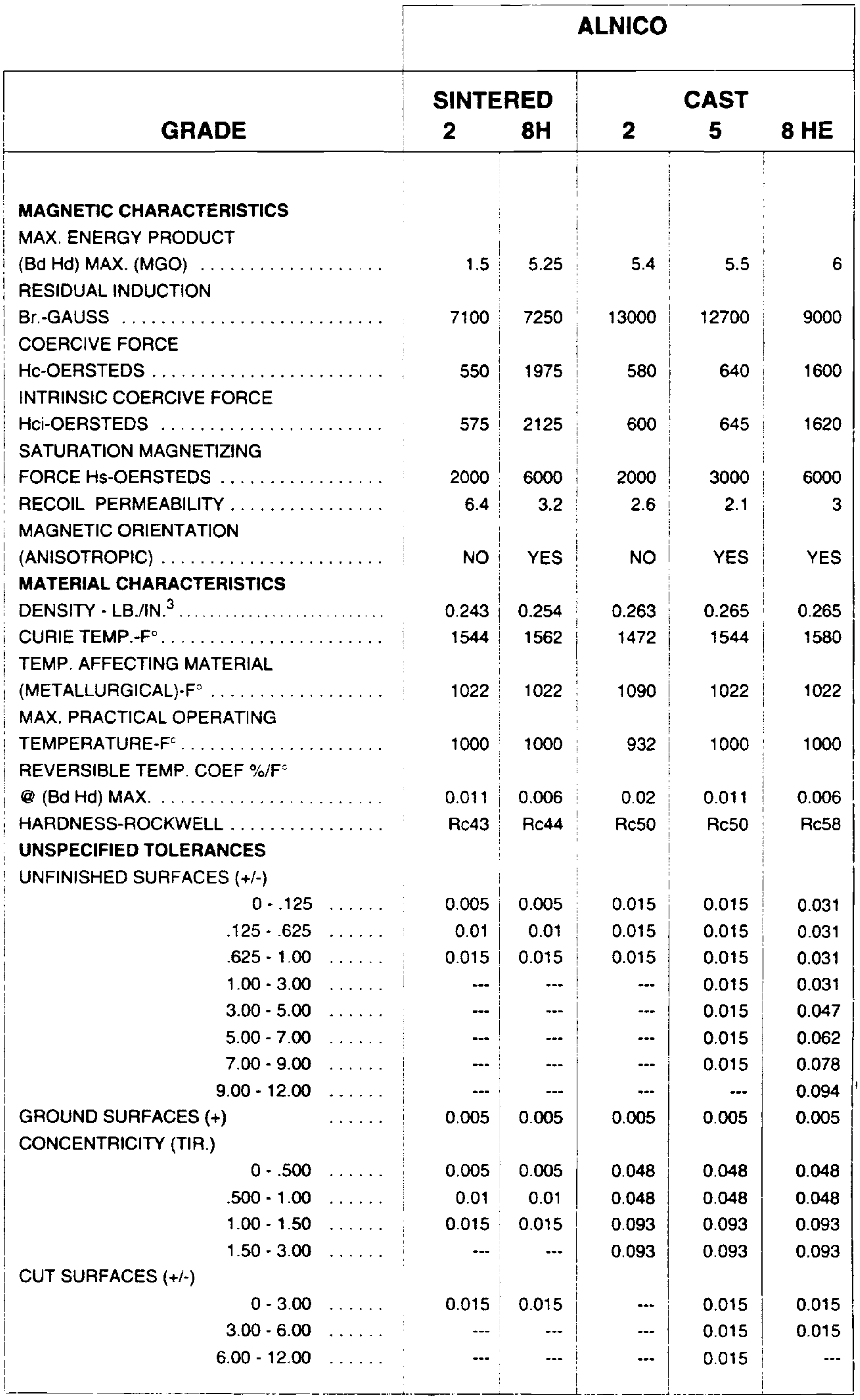
TYPICAL PROPERTIES OF HDPE
(Chanda and Roy, 1993)

	ASTM test method	Polyethylene		
		Low density	High density	Polypropylene
1. Specific gravity	D792	0.91–0.925	0.94–0.965	0.900–0.910
2. Tensile modulus (psi × 10^{-5})	D638	0.14–0.38	0.6–1.8	1.6–2.25
3. Compressive modulus (psi × 10^{-5})	D695	—	—	1.5–3.0
4. Flexural modulus (psi × 10^{-5})	D790	0.08–0.6	1.0–2.6	1.7–2.5
5. Tensile strength (psi × 10^{-3})	D638, D651	0.6–2.3	3.1–5.5	4.5–6.0
6. Elongation at break (%)	D638	90–800	20–130	100–600
7. Compressive strength (psi × 10^{-3})	D695	2.7–3.6	12–18	5.5–8.0
8. Flexural yield strength (psi × 10^{-3})	D790	—	1.0	6–8
9. Impact strength, notched Izod, (ft-lb/in.)	D256	No break	0.5–20	0.4–1.0
10. Hardness, Rockwell	D785	D40–51(Shore)	D60–70(Shore)	R80–102
11. Thermal conduct. (cal/s-cm-K × 10^4)	C177	8.0	11–12	2.8
12. Specific heat (cal/g-K)	—	0.55	0.55	0.46
13. Linear therm. exp. coeff. (K^{-1} × 10^5)	D696	10–22	11–13	8.1–10.0
14. Continuous-use temperature (°C)	—	80–100	120	120–160
15. Deflection temp. (°C at 0.45 MPa)	D648	38–49	60–88	107–121
16. Volume resistivity, ohm·cm	D257	$>10^{16}$	$>10^{16}$	$>10^{16}$
17. Dielectric constant at 1 kHz	D150	2.25–2.35	2.30–2.35	2.2–2.6
18. Dielectric strength (kV/in.)	D149	450–1000	450–500	500–660
19. Dissipation factor at 1 kHz	D150	<0.0005	<0.0005	<0.0018
20. Deleterious media	D543	Oxidizing acids	Oxidizing acids	Strong oxidizing acids
21. Solvents (room temperature) (Cl.H. = chlorinated hydrocarbons)		None	None	None

APPENDIX C

MAGNET SPECIFICATIONS AND DEMAGNETIZATION CURVES FOR ALNICO, CERAMIC, AND RARE EARTH MAGNETS

(Bunting Magnetics Company, 1993)



	ALNICO				
	SINTERED		CAST		
GRADE	2	8H	2	5	8 HE
MAGNETIC CHARACTERISTICS					
MAX. ENERGY PRODUCT (Bd Hd) MAX. (MGO)	1.5	5.25	5.4	5.5	6
RESIDUAL INDUCTION Br.-GAUSS	7100	7250	13000	12700	9000
COERCIVE FORCE Hc-OERSTEDS	550	1975	580	640	1600
INTRINSIC COERCIVE FORCE Hci-OERSTEDS	575	2125	600	645	1620
SATURATION MAGNETIZING FORCE Hs-OERSTEDS	2000	6000	2000	3000	6000
RECOIL PERMEABILITY	6.4	3.2	2.6	2.1	3
MAGNETIC ORIENTATION (ANISOTROPIC)	NO	YES	NO	YES	YES
MATERIAL CHARACTERISTICS					
DENSITY - LB./IN.^{3}	0.243	0.254	0.263	0.265	0.265
CURIE TEMP.-F°	1544	1562	1472	1544	1580
TEMP. AFFECTING MATERIAL (METALLURGICAL)-F°	1022	1022	1090	1022	1022
MAX. PRACTICAL OPERATING TEMPERATURE-F°	1000	1000	932	1000	1000
REVERSIBLE TEMP. COEF %/F° @ (Bd Hd) MAX.	0.011	0.006	0.02	0.011	0.006
HARDNESS-ROCKWELL	Rc43	Rc44	Rc50	Rc50	Rc58
UNSPECIFIED TOLERANCES					
UNFINISHED SURFACES (+/-)					
0 - .125	0.005	0.005	0.015	0.015	0.031
.125 - .625	0.01	0.01	0.015	0.015	0.031
.625 - 1.00	0.015	0.015	0.015	0.015	0.031
1.00 - 3.00	---	---	---	0.015	0.031
3.00 - 5.00	---	---	---	0.015	0.047
5.00 - 7.00	---	---	---	0.015	0.062
7.00 - 9.00	---	---	---	0.015	0.078
9.00 - 12.00	---	---	---	---	0.094
GROUND SURFACES (+)	0.005	0.005	0.005	0.005	0.005
CONCENTRICITY (TIR.)					
0 - .500	0.005	0.005	0.048	0.048	0.048
.500 - 1.00	0.01	0.01	0.048	0.048	0.048
1.00 - 1.50	0.015	0.015	0.093	0.093	0.093
1.50 - 3.00	---	---	0.093	0.093	0.093
CUT SURFACES (+/-)					
0 - 3.00	0.015	0.015	---	0.015	0.015
3.00 - 6.00	---	---	---	0.015	0.015
6.00 - 12.00	---	---	---	0.015	---

Figure C.1 Alnico Magnet Specifications

	CERAMIC			NEO-DYMIUM	
GRADE	**1**	**5**	**8**	**27**	**35**
MAGNETIC CHARACTERISTICS					
MAX. ENERGY PRODUCT (Bd Hd) MAX. (MGO)	1	3.6	3.5	27	35
RESIDUAL INDUCTION Br.-GAUSS	2200	3950	3900	10800	12000
COERCIVE FORCE Hc-OERSTEDS	1825	2400	3200	9800	10500
INTRINSIC COERCIVE FORCE Hci-OERSTEDS	3250	2450	3250	11000	12000
SATURATION MAGNETIZING FORCE Hs-OERSTEDS	10000	10000	10000	30000	---
RECOIL PERMEABILITY	1.15	1.05	1.07	1.1	---
MAGNETIC ORIENTATION (ANISOTROPIC)	NO	YES	YES	YES	YES
MATERIAL CHARACTERISTICS					
DENSITY - LB./IN.^{3}	0.175	0.178	0.176	0.268	0.268
CURIE TEMP.-F°	842	842	842	590	330
TEMP. AFFECTING MATERIAL (METALLURGICAL)-F°	1850	1850	1850	392	392
MAX. PRACTICAL OPERATING TEMPERATURE-F°	480	480	480	180	180
REVERSIBLE TEMP. COEF %/F° @ (Bd Hd) MAX.	0.105	0.105	0.105	0.061	0.067
HARDNESS-ROCKWELL	---	---	---	Rc58	Rc58
UNSPECIFIED TOLERANCES					
UNFINISHED SURFACES (+/-)					
0 - .125	0.01	0.015	0.015	0.01	0.01
.125 - .625	0.01	0.015	0.015	0.015	0.015
.625 - 1.00	0.015	0.015	0.015	0.025	0.025
1.00 - 3.00	0.045	1.5%	1.5%	2.5	---
3.00 - 5.00	---	1.5%	1.5%	2.5	---
5.00 - 7.00	---	1.5%	1.5%	---	---
7.00 - 9.00	---	1.5%	1.5%	---	---
9.00 - 12.00	---	1.5%	1.5%	---	---
GROUND SURFACES (+)	0.005	0.005	0.005	0.005	0.005
CONCENTRICITY (TIR.)					
0 - .500	0.02	0.02	0.02	0.02	0.02
.500 - 1.00	0.03	0.03	0.03	0.02	0.02
1.00 - 1.50	3%	3%	3%	0.03	---
1.50 - 3.00	3%	3%	3%	---	---
CUT SURFACES (+/-)					
0 - 3.00	0.015	0.015	0.015	0.015	---
3.00 - 6.00	---	0.015	0.015	—	—
6.00 - 12.00	---	0.015	0.015	—	—

Figure C.2 Ceramic and Neodymium Magnet Specifications

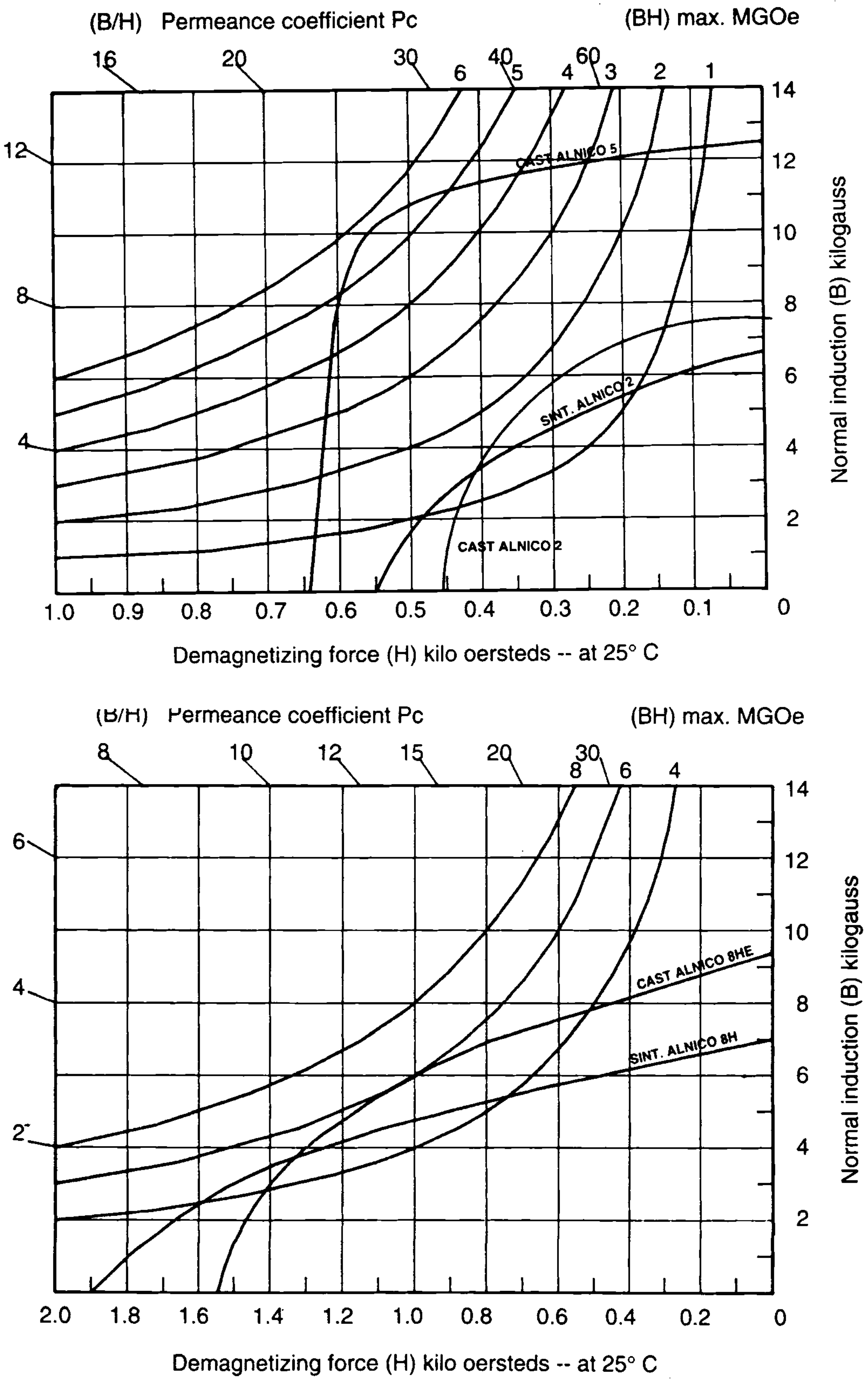


Figure C.3 Demagnetization Curves for Cast-Sintered Alnico Magnets

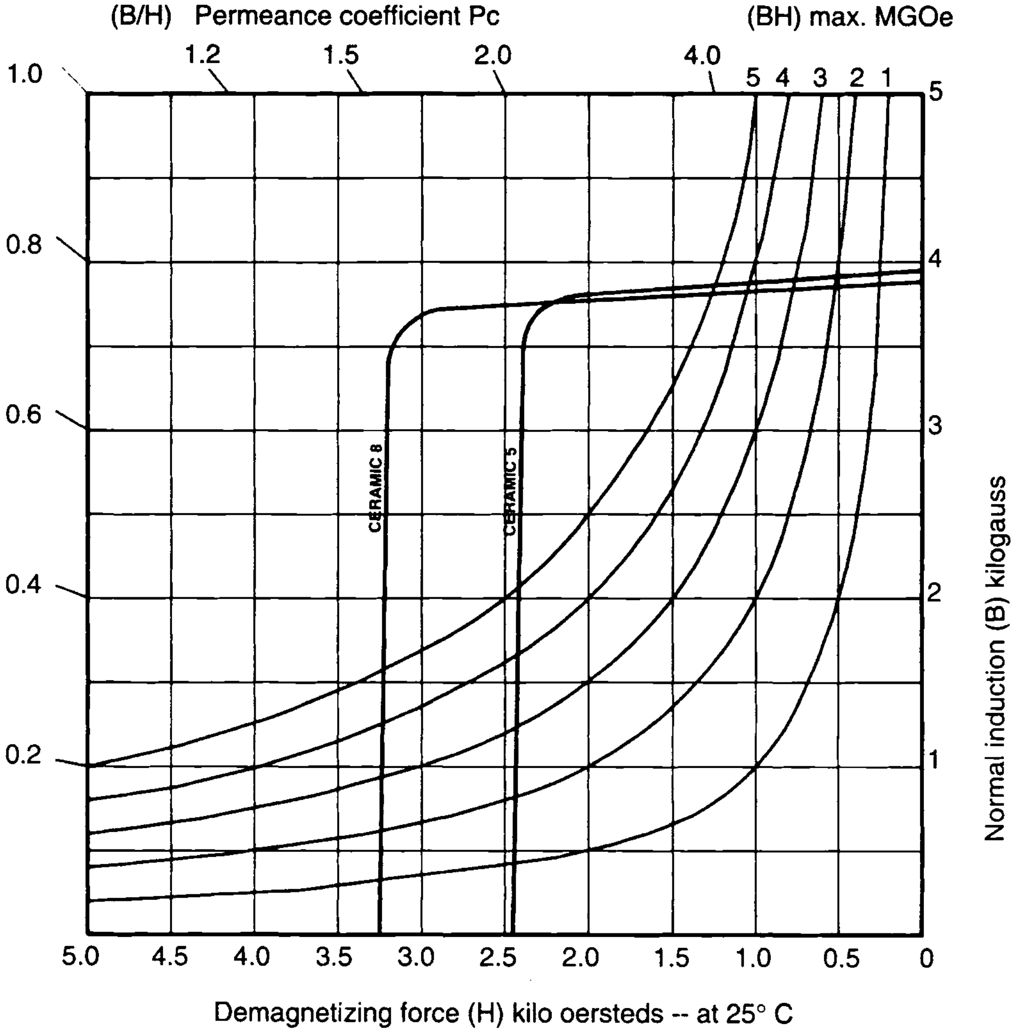


Figure C.4 Demagnetization Curves for Ceramic 5 and 8 Magnets

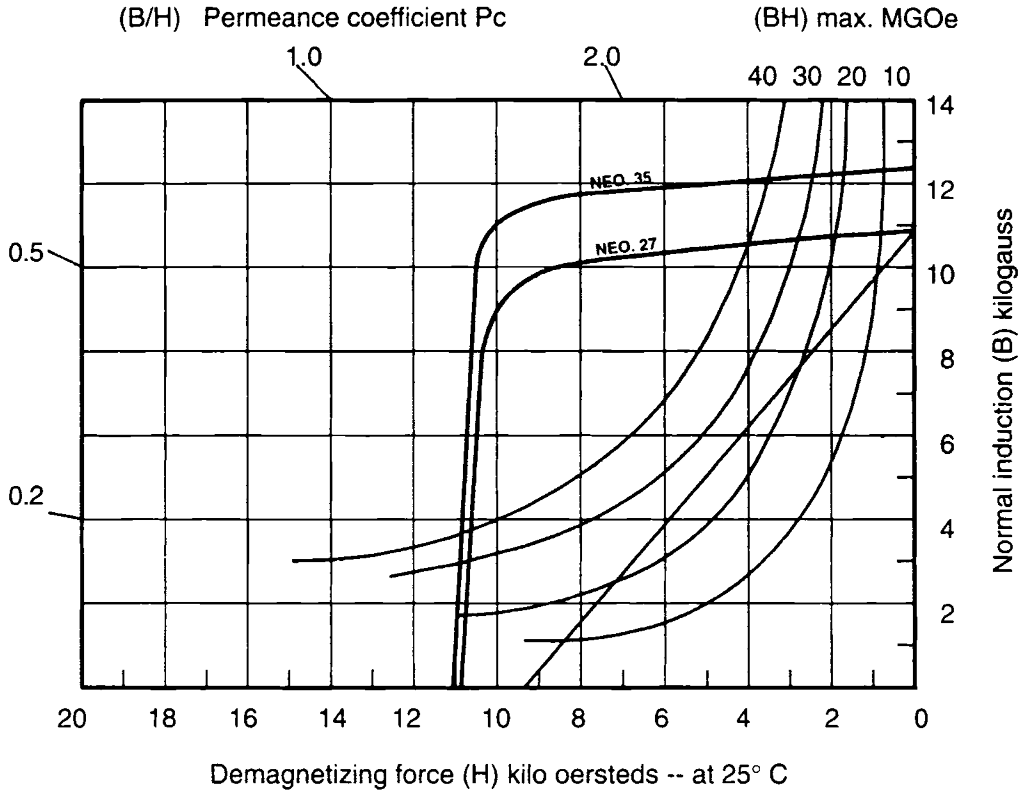


Figure C.5 Demagnetization Curves for Neodymium Magnets

APPENDIX D

INFORMATION ON ISOLATOR
(Lord Corporation, 1993)

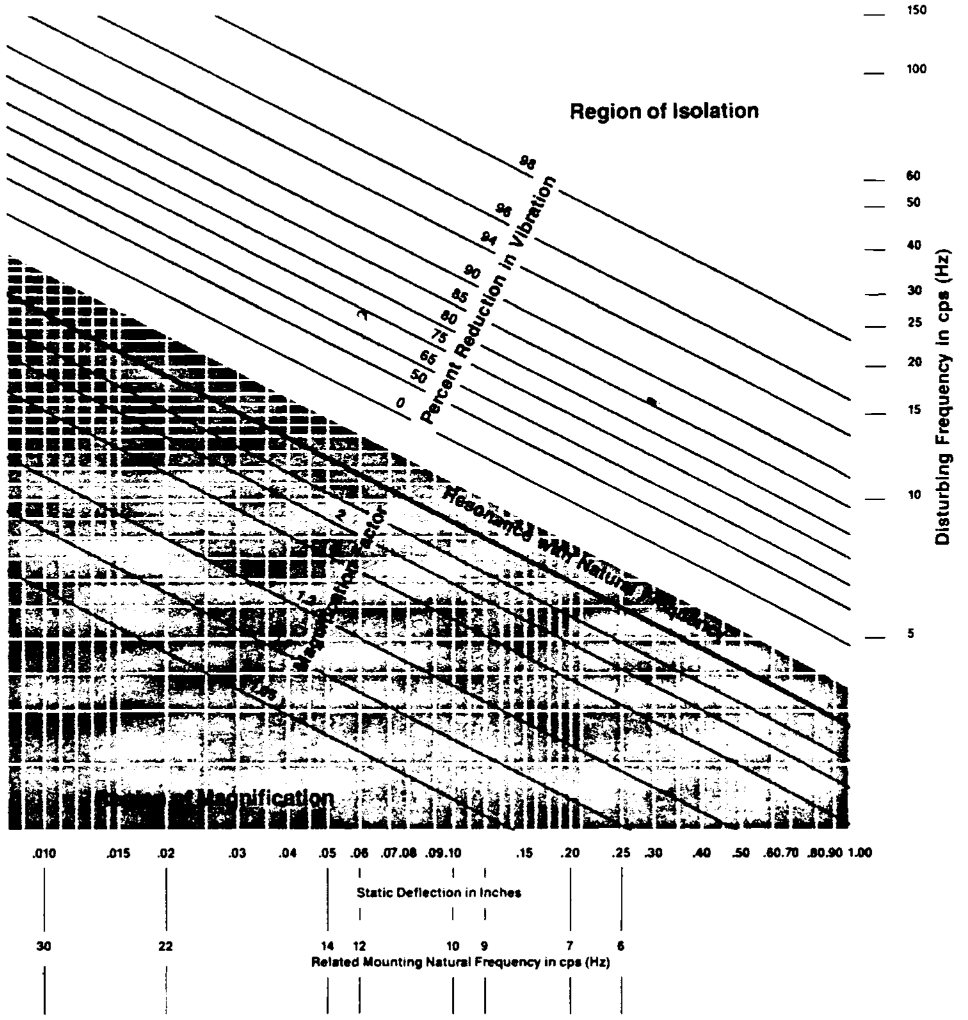


Figure D.1 Isolation Efficiency Curve for Flexible Mounting Systems

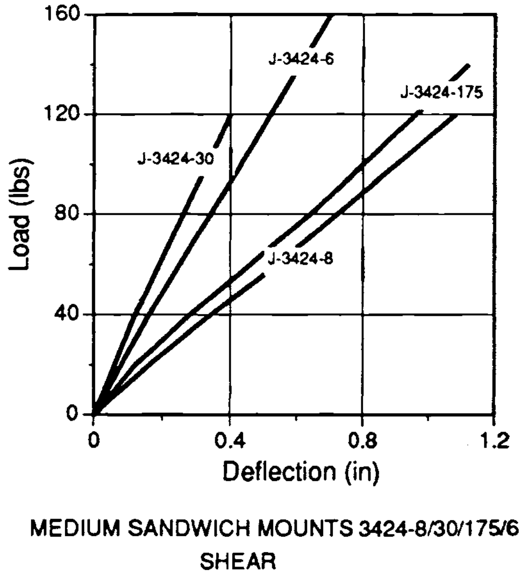


Figure D.2 Load Deflection Curve for Medium Sandwich Mount 3424-8 for Shear

VITA

Sachiko Hashimoto

Candidate for the Degree of

Master of Science

Thesis: SEPARATION OF SILVERWARE FOR MACHINE VISION SORTING AND INSPECTION

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Kobe, Japan, On March 3, 1969, the daughter of Hiroaki and Haruko.

Education: Graduated from Kobe High School, Kobe, Japan in March, 1987; received Bachelor of Education degree in Elementary Education from Osaka Kyoiku University, Osaka, Japan in March, 1991. Completed the requirements for the Master of Science degree with a major in Mechanical Engineering at Oklahoma State University in May, 1995.

Experience: Teaching Assistant, Department of Mechanical and Aerospace Engineering, Oklahoma State University, from August, 1993, to December, 1993; Graduate Research Assistant, Department of Mechanical and Aerospace Engineering, Oklahoma State University, from January, 1994, to May, 1995.