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AN ANALYSIS OF THE CRITICAL PARAMETERS THAT IMPACT
THE SUCCESS OF A BAR CODE SYSTEM

A Thesis
Presented for the
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Degree
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Paul C. Stumb

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ABSTRACT

The technology of bar coding has been in existence for nearly forty (40) years but has only recently found much application in modern industry. This fact is attributable in part to the evolution of the bar coding symbology itself (of which there are at least 16 in use today), but to a larger extent to the technological advances that have greatly improved the ability to both print and read bar coded symbols. The text of this document examines a number of these technological advances and evaluates the contribution or impact of each to the usefulness/success of a bar code system.

While bordering on a taxonomy of bar coding, the first two chapters of the text are intended to provide an overview of a bar code system--its applications and components. The critical elements of any bar code system are defined as hardware, software and environmental/human factors, and it is the complex interaction of these three elements on which the success of a bar code system is contingent.

Although several methods for measuring the success of a bar code system are certainly plausible, the most appropriate or revealing index of success is identified as First Read Rate (FRR), for a low FRR will virtually guarantee user rejection of the system in favor of a more traditional yet undoubtedly slower and less accurate method of data collection or reporting. But while the importance of a high FRR is generally accepted, the factors or parameters that impact FRR are to a large extent still unknown.

As each of the three major bar code system components are examined, two categories of associated parameters are identified. These are:

1. GO/NOGO Parameters
2. Level of Success Parameters

Of the "level of success" parameters, the quality of the printed media or print technique is often purported to be the single most important criterion in determining FRR. Other potentially significant contributors to the success of a bar code system, however, include the bar code application (defined herein by label length), and the human variability of the operator(s) that must use the system.

Chapter III of this text outlines an experiment designed to characterize the impact of these three parameters on the FRR of a bar code system. In Chapter IV, a mixed-effects linear model is defined, and factorial analysis of variance (ANOVA) techniques are used to analyze the results of 4800 attempted "reads" which represent the FRR data for every possible combination of four (4) print techniques, three (3) application/label lengths, and two (2) randomly selected operators.

Contrary to the assertions of many "experts", the results of this experiment lead to the conclusion that the operator effect and the interaction effects between operator and the other experimental variables are likely to have the greatest impact on a system's FRR. This conclusion suggests that success of the overall system is tantamount to success in controlling the operator variability, and that more attention should be given to the definition of human factors such as

operator training than to the specification of system hardware--as is so often the case.

The text of this document concludes with some recommendations for additional experimentation and research in this field, and finally with an assessment of future trends with respect to the technology of bar coding and in a broader sense the entire field of automatic identification.

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CHAPTER I

INTRODUCTION--AN OVERVIEW OF BAR CODING

A. What Is a Bar Code

Bar codes are a printed bar and space representation of digital data configured to represent numeric or alphanumeric information. . . . An analogy of the bar code is to consider it as a pulse code modulated signal where linear distance on the print medium is equivalent to time, and the white and black reflectance levels of the bar code pattern are equivalent to high and low logic levels.

[KRAUSE, WALKER, #31-4]

While the above definition may adequately define the term "bar code" it cannot begin to provide an appreciation of the tremendous usefulness or impact that the concept of bar coding has had and most likely will continue to have on so many aspects of today's technology oriented world. Dr. Thomas V. Sobczak, a renowned consultant in the field of Automatic Identification, supports this assertion with his comment that "Bar coding (symbols and coding systems) is not only a part of the factory of tomorrow, it is a part of the factory of today" [SOBCZAK, #44-3]. In fact, the technique of bar coding has in recent years found popularity in:

- The automotive industry (there are 28 bar codes on every new GM auto manufactured today);
- The airline industry (a form of bar coding is still used in some areas to identify luggage);
- The grocery industry (where the UPC code enjoys its most prominent role);

- Hospitals and the health care industry in general (where many blood banks are now using bar codes);
- Libraries, and
- numerous other manufacturing, warehousing, retail, and distribution facilities.

B. Why Use a Bar Code

In an era where cost reduction to maintain competitiveness is quickly becoming a must rather than simply a nicety, automatic identification techniques such as bar coding have increased not linearly but exponentially both in popularity and more importantly in usefulness to modern industry.

A significant fraction of the total cost of a product [anywhere from 30 to 85% as estimated in a study performed by the Material Handling Institute] is the cost of the material flow cycle. Automatic identification gives better control of the material flow cycle: receiving; inventory management; material movement; production; packaging; warehousing; shipping.

[SHARKEY, #41-1]

Wherever words such as Factory Automation, Automated Storage and Retrieval Systems (ASRS), Automated Inventory Control, Computer Integrated Manufacturing (CIM), and Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) are used, one is likely to find mention of bar coding as well. This is simply a result of the fact that many managers are now realizing the tremendous benefits that automatic identification and, in particular, bar coding can provide them.

"Automatic Identification technology is a proven, well established method for improving productivity" [SHARKEY, #41-1]. The goal of any

automatic identification technique is to facilitate the accurate identification of an object by lessening the need for human effort and placing the onus of recognition on a less fallible, inanimate machine. The benefits that may be realized as a result of achieving this goal (i.e., implementing a successful automatic identification system) are basically two fold:

1. Increased speed of data collection; and
2. Improved accuracy/reliability of data collected.

These benefits translate into dollars saved both in terms of the labor required to initially collect the data, and the labor required to resolve the problems caused by erroneous or misidentified data. Or as another author states, "the speed and accuracy of bar code often will turn a bottom line from red to black and that is the prettiest line of all in a bar code system" [ADAMS, #5-6].

As an indication of the effectiveness of bar coding in improving the reliability of data, one needs only to compare the accepted standard error rates associated with manual/keyboard data entry, OCR, and bar coded data collection.

Date Collection Method	Estimated Substitution Error Rate	Equivalent Percent Errors
A. Manual/Keyboard	1/50 - 1/400 characters	2%-0.25%
B. OCR	1/10,000 characters	$1 \times 10^{-4}\%$
C. Bar Code	1/2.7 - 1/70 million characters	$3.7 \times 10^{-7}\%$ - $1.4 \times 10^{-8}\%$

With respect to the speed of data collection, it is easy to see how reported improvements of more than 1200% could be realized with the use of a laser bar code scanner (to be discussed later) in a warehouse with more than 12,000 unique parts to be inventoried. A more common example might be the grocery industry, where improvements are measured in terms of reduced check out queues or the requirement for fewer cashiers. Since the introduction of bar coding to the grocery industry in the early 1970's (see Figure I-1), many stores have experienced a reduction in service time (i.e., check out time) of as much as 400%.



Figure I-1. Cartoon Depicting the Use of Bar Coding
in the Grocery Industry
Source: Good Housekeeping, #22-19.

C. Bar Coding As ONE Method of Automatic Identification

There's nothing new about codes and symbols. The ancient Phoenicians developed cuneiform to uniquely identify their trade goods. Gold and silver smiths, firearm makers, and potters have long used symbols to sign their work. In 1932 a dissertation was written on the need to automate grocery stores, but we had to wait until after World War II, and micro-electronics, for the technology to make it possible for machine readable symbols to become wide spread.

[NELSON, #34-1]

While arguably the most popular and most widespread technique, bar coding is but one of many methods of automatic identification in existence today. Other significant techniques include: (1) Optical Character Recognition (OCR), (2) Magnetic Ink Character Recognition (MICR), (3) Magnetic Stripe Technology, (4) Radio Frequency Transmission (RF), (5) Surface Acoustical Wave Transmission (SAW), (6) Weigand Technology, (7) Voice Recognition, and (8) Vision Systems. Without devoting too much space or attention to these other methods of automatic identification, the "pros" and "cons" of each as compared with bar coding should be understood and are, therefore, examined briefly below.

1. Optical Character Recognition (OCR)

This coding system, which has been in use for about 20 years, was adopted by the National Retail Merchants Association (NRMA) to encode garment sales at the retail level. It is also now used in many department stores. While the machine readability of OCR is less reliable than bar code (primarily because OCR readers are more sensitive to and less forgiving of the variability of human hand motion), its human readability may be a requirement for certain applications. Additional

advantages of OCR include the facts that it is easy to print, easy to copy, and can support a high information density. Disadvantages, however, include its restricted character set, a typically high error rate, and the requirement for contact scanning (i.e., it cannot be read from a distance).

2. Magnetic Ink Character Recognition (MICR)

Evidence of this technology is most prominent in the banking industry, where millions of checks each month are quickly processed via magnetic ink identification. While the machine readability of MICR code is very good, the maximum code density is only about 8 characters/inch and an MICR reader is very expensive (approximately \$100,000).

3. Magnetic Stripe Technology

Magnetic Stripe recording is not really all that different from printing bar codes. In magnetic materials there is a two-state choice of polarity, just as there is a two-state choice between either black or white in many printing processes In both circumstances information is delineated by the locations on recording media where there are either plus/minus flux or black/white color changes.

[BURKE, #12-110]

Advantages of magnetic strip (often abbreviated as simply mag stripe) include the ability to encode much more information in a smaller physical space than bar coding (i.e., magnetic information can be packed more densely) and the ability to easily encode the full ASCII character set. Disadvantages of the technology, however, include the fact that mag stripes are not human readable and cannot be read from a distance. They are

also slow and somewhat expensive to print, and after being printed the media is easily modified (i.e., not too secure) or accidentally erased or destroyed by even a relatively weak magnetic field. Magnetic stripe technology has, nevertheless, enjoyed popularity in several significant applications including identification for manufacturing work-in-process travelers (typically replacing IBM hollerith cards) and on "secure-ID" cards used by automated bank tellers and others.

4. Radio Frequency Transmission (RF)

The components of any RF system include a control unit, an antenna, and a code tag. The antenna transmits a microwave signal which is reflected and frequency modulated by the tag. Most tags are "passive," and once encoded with information they cannot be altered. Some expensive "active" tags, however, provide for the changing, addition, or deletion of encoded information after receipt of the appropriate key code. Benefits of an RF system include the insensitivity of tags to harsh environments and the ability to read through either solid objects or open spaces (i.e., neither physical nor direct line of sight contact between the reader and the tag is required). Deficiencies, however, include the lack of human readable information on a tag, the cost of a system (especially the marginal cost of just a few tags), and the inability to read or decipher information when more than one tag is in the field of view or "capture window" of the reader.

5. Surface Accoustical Wave Transmission (SAW)

Except for the method of sending and receiving signals, this technique is very similar to, and has the same advantages and disadvantages as RF transmission. In a SAW system, a tag is encoded by the laser etching of an interdigital transducer (IDT) on its surface.

6. Wiegand Technology

Invented by John R. Wiegand, the Wiegand Effect technology or at least the worldwide rights to the technology were recently purchased by the Echlin Manufacturing Company of Branford, Connecticut. The technology is based on the properties of a specially work hardened ferromagnetic wire that is wound around an also magnetic soft inner core. A rapidly applied external magnetic field generates a large change in flux in this "Wiegand wire." The magnetic polarity of the soft inner core changes much more quickly than the hardened shell--thus, inducing a voltage pulse of approximately one volt in an external sensing "pick-up" coil. The appropriate arrangement of these wires usually in a laminated card results in a series of digitally encoded binary pulses. Advantages of the Wiegand technology include: no requirement for an external power source, no moving parts, and the permanency of information (i.e., the encoded data cannot be altered or erased without physical destruction of the media). This technology which is used most often for security related applications such as

credit cards, access control cards, and employee badges, is somewhat expensive to produce and, because it must be secured from an outside vendor, lacks the flexibility of bar coding which can easily be produced in-house.

7. Voice Recognition

While really still in its infancy, this technology has been dreamed about and slowly developed for many years. It is, however, still very limited and is usually designed to accommodate either a very limited vocabulary or a very limited (usually 1) number of users. Its primary applications today are in the areas of: Security, and Toys/Games.

8. Vision Systems

While OCR and bar coding are each arguably machine vision systems, the generic item "vision system" is usually applied to linear or area scan systems that employ the technique known as pattern matching--in which two dimensional arrays of pixels are scanned and compared with preprogrammed arrays in a computer's memory. The cost of a vision system reader varies from a high \$25,000 for a line scanner to an astronomical \$300,000 for an advanced area scanner.

D. The Variety of Bar Codes

Even within the boundaries of bar coding, there are at least 28 unique symbologies. Again without focusing on the details of each bar code type, some of the most significant distinguishing characteristics of each are highlighted below.

1. Automatic Car Identification (ACI)

This code selected by the American Association of Railroads, is used to identify more than 2 million railroad cars scattered across more than 255,000 miles of track. The application of car labels alone, which began on October 10, 1967, took more than seven years.

2. Binary Code

This code has been popular for years in the paper products industry. Companies such as Scott paper in Philadelphia are using the code to mark outer boxes and shipping containers.

3. Codabar

One of the most used symbologies, Codabar is the unofficial standard for library systems and is used by the Library of Congress for circulation and document control. This symbology developed by a division of Pitney Bowes is also used by the American Red Cross and other agencies for blood control, and Federal Express uses the code to process more than 450,000 packages per day. It is a discrete, numeric-only code which employs four bars and three spaces per character. Because, however, Codabar includes 18 unique bar widths (that aren't even multiples of units), it is more difficult to print than most other symbologies.

4. Binary Coded Decimal (BCD)

This code is used primarily in the meat packing and slaughterhouse industry. In this numeric only code, a wide bar is equivalent to a binary "1" and a narrow bar equals a "0".

5. Modified Binary Coded Decimal (MBCD)

A direct derivative of the BCD code, MBCD employs the same bar value scheme (wide = 1, narrow = 0) as its predecessor. The only difference from the standard BCD is in the relative positional values assigned to each bar. While both use 4 bars per character, the format of the BCD code is 8-4-2-1 while the MBCD format is 7-4-2-1. Little practical application is made of this code.

6. Two Out of Five Code

Often referred to as "the forgiving code" because the possibility of a false read or character transposition error is virtually nonexistent, Code 2 out of 5 is popular for many applications. In addition to its industrial production planning and control uses, it is used extensively for toll road shipper recording, airline ticketing, baggage and cargo handling, and photofinishing envelopes. The numeric-only code was created in 1968 by Gerry Woolf of Identicon Corp, and it is relatively inexpensive to implement.

7. Interleaved Two Out of Five Code

A very densely packed code, Interleaved 2 out of 5 is functionally equivalent to its big brother 2 out of 5, except for one key addition. InterLeaved 2 out of 5 does not only encode characters in the bars but also uses the spaces between the bars to convey information. By varying the width of the spaces as well as the bars, Dr. David Allais, the code's inventor, was able to virtually double the code density of the 2

out of 5 code. Although the nature of this code will accommodate only an even number of characters, leading zeros are often used to offset this problem.

8. Ten Segment Decimal Code

Developed by Accu-Sort Inc., this code is used in many process applications. Bausch and Lomb, Corp. and the FDA (for Lot Label Control) are two of the more prominent users of this symbology.

9. Wagonwheel or Sunburst Code

This nonlinear (as the name might imply) code was one of the original contenders for the title "Universal Product Code (UPC)." While difficult to print, it is perhaps the most dense code ever developed (i.e., it allows for the greatest amount of information in the least amount of space).

10. Double Track Symbol Code

This code makes use of the 4 bar/character scheme (format 8-4-2-1), but instead of a variable width bar--it uses two tracks of bars. A bar in the upper track equals a binary 1 and a bar in the lower track equals a binary 0. This symbology is used primarily for marking outer shipping containers.

11. Distribution Symbol (DS)

While not yet practicable for use on corrugated boxes, this UPC based code is intended for use on outer shipping containers. It is being promoted by the National Association of Wholesalers and Distributors.

12. Bullseye Code

Introduced by Norman Woodland and Bernard Silver on October 20, 1949, this nonlinear code was the first symbology to receive a U.S. patent. A derivative, developed by RCA for the US Postal Service, was also an original contender for the Universal Product Code (UPC) title. Currently the Post Office uses this code at 21 major bulk mail centers to scan approximately 2,700,000 packages per day.

13. Telxon Code

Used primarily in the grocery store industry to ensure name brand products don't lose shelf space or position when shelves are reloaded, the Telxon code is used in conjunction with the Universal Product Code (UPC). While already in use in many stores, it is not used to label products--but rather shelf space only. Variants of the Telxon Code are the MSI code, the Anker code, and the Plessey code--all of which are based on pulse width modulation (discussed below).

14. Digital Code

The Digital Code utilizes a horizontal (as opposed to the standard vertical) bar orientation. Each bar of the Digital Code represents one arabic number. While simple in concept and relatively easy to print, the code is in many ways similar to OCR for each bar must be entirely covered by the scanner. The Digital Code, however, is not easily human readable as is O.C.R.

15. Frequency Code

The most common example of a frequency code is the F2F code (also called Norand). The F2F and, in fact, most frequency codes are binary and based on a transition from black to white. A specified bar width is determined, then two adjacent bars (black) are the binary equivalent of a one and a bar-space transition is equivalent to a zero. Like most binary based codes, F2F requires 4 bars per character.

16. Octal Coded Decimal (OCD)

Another binary based code, OCD is based on a 3 bar/character set with a 4-2-1 format. Similar to BCD, OCD employs the wide bar equals 1, narrow bar equals 0 value assignment.

17. Code 11

An indirect derivative of Code 2 out of 5, Code 11 is marketed by Intermec and was designed for applications with tight printing area constraints such as very small AT&T telecommunications components. The name stems from the 11 elements in the character set of this code (i.e., the 10 digits and the dash symbol).

18. Pulse Width Modulation Code

The PWH code is the best example of a Pulse-Width-Modulation Code; it was originally developed by Plessey Company Limited of Dorset, England. This symbology, the predecessor to the Frequency Code, is based on the relative positions of two bar widths. A wide bar followed by a narrow space is equivalent

to a binary 1; and a narrow bar followed by a wide space is equivalent to a binary 0.

19. Universal Product Code (UPC-A,B,C,D,E)

The symbology used for virtually all supermarket and grocery store product identification, the Universal Product Code (UPC) was adopted as an industry standard on April 3, 1973, and is almost certainly the best known and most widespread application of bar coding in existence today. "By 1980 . . . better than 90% of all grocery items carried a UPC code . . . by May 1986, there were approximately 10,500 supermarkets using UPC symbol-based point-of-sale systems" [HARMON, ADAMS, #24-20]. The code is a 10-digit numeric only code (i.e., no alpha characters) in which the first five digits serve as a unique identifier for the manufacturer and the last five digits denote the particular product.

20. European Article Numbering (EAN)

The EAN symbology which is nearly identical to the UPC is also known as the World Product Code (WPC). It was adopted as a European standard in December 1976, as a result of the then just emerging success story of the UPC in the U.S. The EAN differs from UPC only in that the first two characters in an EAN symbol are used to denote a country.

21. Code 39 or Code 3 of 9

Code 39, which is quickly becoming the defacto standard for industrial/manufacturing applications of bar coding was developed by Ray Stevens and Dr. David Allais of Intermec (formerly

Interface Mechanisms) in 1975. Each character of the code consists of 5 bars and 4 spaces. Of these nine elements (bars and spaces), 3 are wide and the other 6 are narrow--hence the term 3 of 9. The relative position of the 3 wider elements correspond to a particular character. The number of permutations of wide bar positions allows for a unique pattern for all alpha and numeric characters plus several special characters as well. Coincidentally, the original Code 39 character set included exactly 39 unique characters. Currently, however, the set consists of 43 characters (the 10 digits, 26 letters, space, - , . , \$, / , + , and %). In addition, Code 39 is a discrete (meaning the intercharacter gap is insignificant) and bidirectional (meaning the code may be scanned in either direction) symbology.

22. Code 93

A derivative of the popular code 39, this code was introduced by Intermec in April 1982, to support applications that require a higher density alpha-numeric symbology. In fact, code 93 is regarded today as the highest density alpha numeric code in existence. Its character set is identical to code 39 but instead of two bar widths, four unique bar widths are employed by the symbology.

23. Code 128

A competitor of code 93 this symbology is another highly compressed alpha numeric code that was introduced by Computer

Identics in the Fall of 1981. In addition to the capability of encoding all 128 ASCII characters, code 128 is able to substitute pairs of digits (i.e., "00", "11", "22", . . .) in place of single alpha characters. This feature is particularly useful in compressing data for some specialized applications.

24. Telepen

Introduced in 1973 by S. B. Electronic Systems, Ltd. in Harpenden, Hertfordshire, England, this code is principally responsible for the local development of both code 93 and code 128 several years later. Like code 128, it was designed to include the entire ASCII character set, and employs the double density numeric feature whereby a single ASCII character may be substituted for pairs of digits.

25. Code 2 of 7

This code also known as the Ames code is a derivative of Codabar. The object of this code is to simplify the Codabar symbology by reducing the number of unique bar widths from 18 to 2.

It may also be interesting to examine briefly the heritage or evolution of linear bar type symbols. Figure I-2 is provided to portray the progressive sequence of development.

THE EVOLUTION OF LINEAR BAR CODES

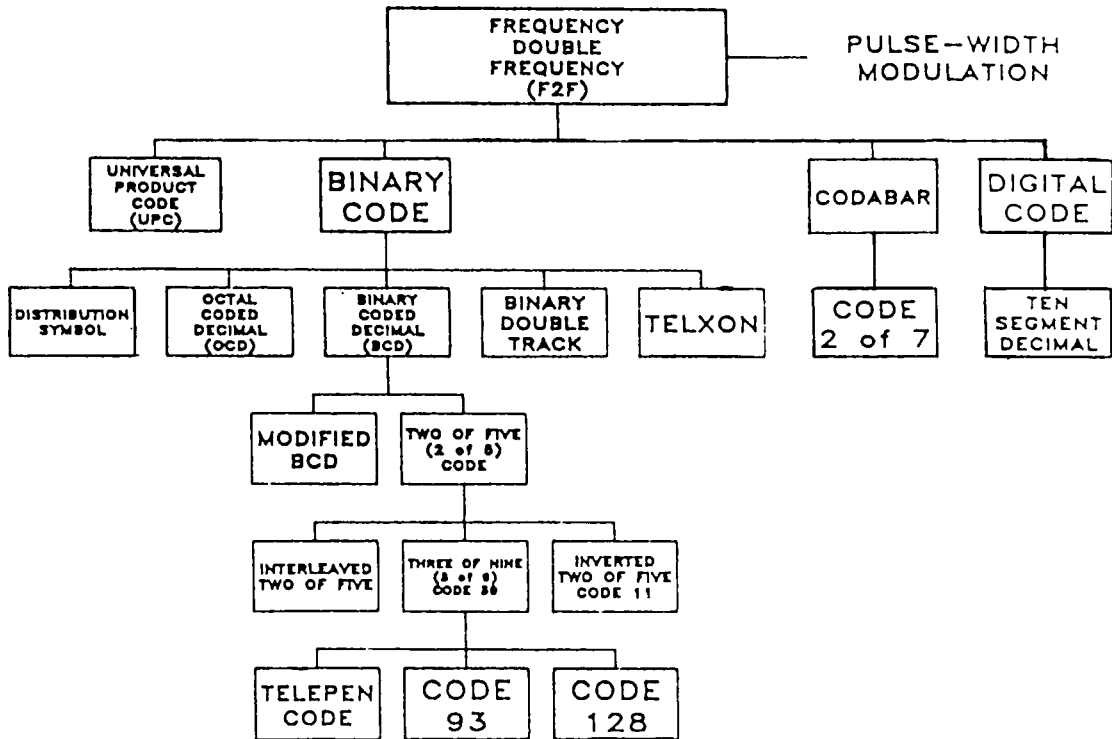


Figure I-2. The Evolution of Linear Bar Codes

E. Standards for Bar Coding

To permit automatic identification of every item at every point in the distribution process, the grocery industry and its suppliers adopted a UPC standard code format. This standardization greatly encouraged the growth and success of bar code scanning in the supermarket. Recognizing this vital role of standardization, other industries and government agencies began considering code format suited to their applications. Today standard code formats exist within the: Department of Defense--Code 3 of 9, Automotive Industry--Code 3 of 9, Health Care Industry--Code 3 of 9, retail and Wholesale Distribution--Code Interleaved 2 of 5.

[ACCU-SORT SYSTEMS, INC., #1-1]

To a large extent, because of its adoption by the Automotive Industry Action Group (AIAG) and the U.S. Departments of Defense (DOD) and Energy (DOE) (as described in Mill Standard 1189), code 39 is quickly replacing all other contenders as the leading standard for industrial and manufacturing applications. In fact, many experts believe that "It [Code 39] is rapidly becoming 'The Code' for industrial and commercial applications" [HARMON,ADAMS, #24-16]. For this reason, the remainder of this document will focus primarily, if not exclusively, on Code 39. And while many of the principles examined herein may apply to many or all bar code symbologies, the basis for the subsequent narrative may be safely assumed to be Code 39.

CHAPTER II

THE MAJOR COMPONENTS OF A BAR CODE SYSTEM

A. Definition of a Bar Code System

Although, as already discussed, the technology of bar coding is now used in receiving, inventory management, personnel identification, shop floor data collection, packaging, shipping . . . the major components or elements of each of these unique applications are really very similar. The common elements included in each of these and, in fact, in any other bar code application are:

1. A bar code symbology;
2. Printed, etched, or otherwise marked bar code media;
3. Equipment to scan or read the bar code;
4. An algorithm to decode the encoded information;
5. A destination for the decoded data (e.g., a database, electronic file . . .);
6. People to use or monitor the equipment; and
7. An environment in which the equipment and media are used.

These elements may be combined into three mutually exclusive categories. These are: hardware, software, and environmental/human factors. The combination and definition of the specific hardware, software, and environmental/human factors associated with a bar code application constitutes a "bar code system."

B. Hardware

The hardware associated with a bar code system is at a minimum a bar code reader and a printer, and may (and in fact usually does) include other pieces of Automated Data Processing Equipment (ADPE) hardware such as a host computer, a multiplexor or port concentrator, and various communication/interface hardware.

1. Bar Code Printers and the Measurement of Print Quality

The first piece of bar code system hardware to be addressed is the bar code printer. In this area especially, the recent technological advances have been phenomenal. Current methods of printing bar codes include:

Dot Matrix	Phototypesetting
Square Matrix	Ink Jet
Thermal	Electrostatic
Thermal Transfer	Wet Ink
Laser	Hot Stamp
Formed Font Impact	

The choice among these various alternatives depends on several factors--the desired quality of the output, the speed required of the printer, the size and volume of the media to be printed, the number of times the media might be (i.e., is expected to be) used or scanned, the environment in which the media will be used, the physical space requirements (and more importantly communication interface requirements) of the printer itself, plans or requirements for flexible use of the printer for other applications (versus dedicated to printing bar

codes), and of course the cost of the unit and associated peripherals/supplies/and maintenance.

Prior to the age of the microprocessor, hot stamping with metal plates or wet ink and mats were really the only two alternatives available for printing bar codes (see Figure II-1). Because these processes require a molded or etched rubber (for wet ink) or metal (for hot stamp) plate for each legend, neither process is well suited to printing information with a high degree of variability as is required for most modern industrial bar code applications.

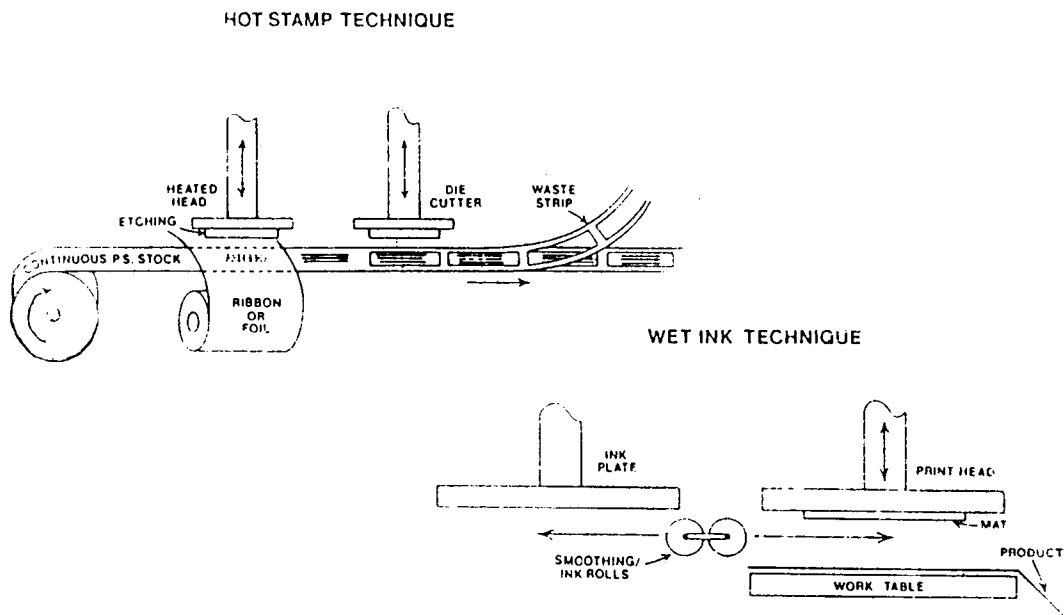


Figure II-1. Hot Stamp and Wet Ink Printing Techniques
Source: NELSON, #34-16-17

The development of the microprocessor has, however, made possible the introduction of a variety of new and improved printing techniques.

The dot matrix printer (Figure II-2) is a highly flexible, inexpensive device that is capable of printing low resolution, low density codes on virtually any sized paper media. The dot matrix print head consists of a series of pins arranged in a rectangular matrix (usually 5 x 7 or 7 x 9). A microprocessor is used to fire the appropriate pins at the appropriate time to form characters or bars as the print head moves across the paper print media. Because by definition, dot matrix printers print a series of dots, good vertical edge definition for bar coding is difficult to achieve. The recent introduction of the square matrix printer which operates under the same principles as its older brother but with square pins in its head has somewhat alleviated this problem.

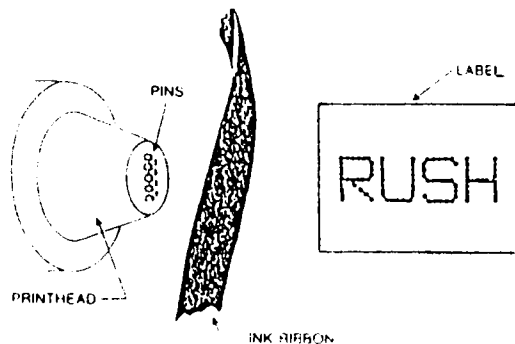


Figure II-2. Dot Matrix Printing Technique
Source: NELSON, #34-20

In addition to its low cost, the biggest advantage of the dot/square matrix printing technique is its tremendous flexibility. Subject only to the skill of the programmer, a dot matrix printer can be used to print virtually any bar code symbology, in any orientation, and intermixed with any other text or characters.

Another type of impact printer is the formed font printer (Figure II-3). While much less flexible and more expensive than the dot/square matrix printers, the formed font provides for much higher quality and quantity output. Similar to the office typewriter, the formed font printer has individually formed characters that are etched into a rotating metal drum. Microprocessor driven hammers are used to press a paper media against a dry ink ribbon (also similar to that on a typewriter) which in turn is forced against the appropriate set of bars or character on the rotating drum. Because each bar is precisely etched into the metal drum, the bar width, spaces between bars, and edge definition are accurately maintained. While this technique allows for the generation of high quality, high density bar codes, flexibility is very limited. The bar code may only be printed in one orientation (because the drum is fixed) and any other printed information (such as human readable text) is limited to the formed characters that are provided on the drum.

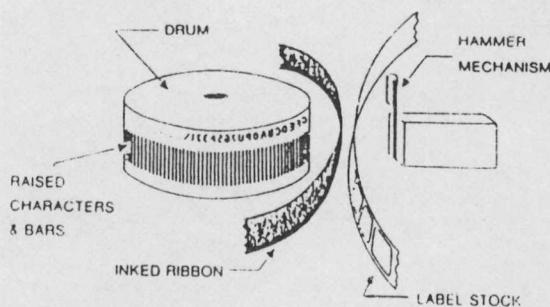


Figure II-3. Formed Font Impact Printing Technique
Source: NELSON, #34-19

In contrast with the relatively fast and noisy impact printers is the somewhat slower and much quieter thermal printer (Figure II-4). The thermal printer which requires a special (and relatively expensive) heat activated paper media uses a heated print head which causes a chemical discoloration in the specially sensitive media. Different elements or segments of the print head are alternately heated and cooled under microprocessor control to burn or print variable information. While this technique provides excellent edge definition and print quality, the Print Contrast Signal (PCS)--to be discussed later--can sometimes be a problem, as can the durability of a thermal label--especially when exposed to excess heat, light, or other strong sources of radiation.

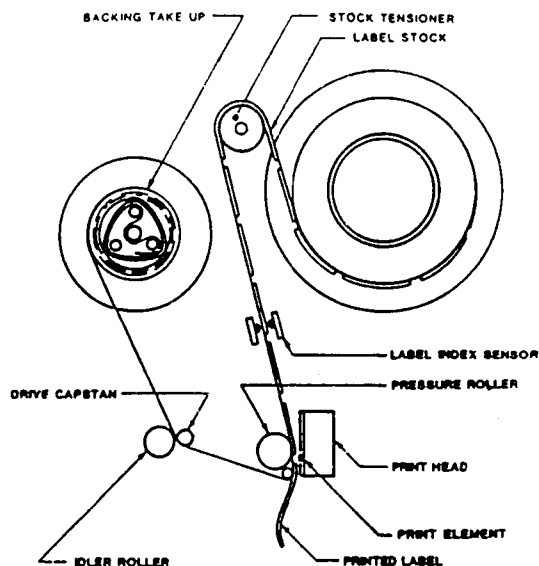


Figure II-4. Thermal Printing Technique
Source: NELSON, #34-21

An off-shoot of thermal printing is the technology known as thermal transfer. Thermal transfer printing is based on the same concept as thermal printing--but it does not require any special paper or media. Again the original quality of media printed using the thermal transfer technique is typically superb, but the durability of this media is also poor--especially after many reads or attempted reads with a contact probe (i.e., the print surface is easily marred).

Electrostatic printing (Figure II-5) is another new and exciting print method made possible by the advent of the microprocessor. This technology is very similar to that of an office copier, for both employ a dielectric transfer drum. The difference is in the requirement of a master/original copy. The "master" for the electrostatic printing of codes and/or other characters consists of a set of preprogrammed instructions that are typically stored in interchangeable memory fonts. The preprogrammed fonts provide instructions for electrically charging either the drum or the paper media. The charged areas then attract a dry toner which is permanently affixed by heat (or sometimes by pressure) to the paper. This printing technique is relatively fast, quiet, and very flexible (with respect to the size and/or orientation of characters). And while the cost of these printers has fallen considerably in recent months, they are basically page printers and are not well-suited to printing the smaller bar code labels which are required for many applications.

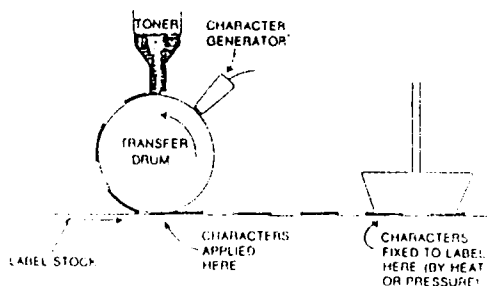


Figure II-5. Electrostatic Printing Technique
Source: NELSON, #34-18

While Hewlett-Packard and others are now marketing low cost electrostatic printers under the guise of "laser printers" (e.g., the HP Laserjet 1200), this is really just a confusing misnomer, for the concept of laser printing is an altogether different technology that is also now being used to print bar codes. The LASER technology (Figure II-6) is used in two different ways for printing. First, a high powered laser may be used to physically etch or carve information (bars and/or characters) into a solid material such as steel or aluminum. Secondly, a low powered laser may be used to burn through a colored surface coating to reveal another different colored material underneath (e.g., anodized aluminum).

The durability of such laser etched or engraved bar codes is undoubtedly better than any of the other printing methods previously discussed, but the anodized or coated metal tags are often difficult to attach to an object or material and are expensive, and the laser etching of a bar code into a solid piece of material often does not produce a high enough "Print Contrast Signal" (PCS) or differentiation between

the dark and light bars to be reliably decoded. Also, while reasonably fast, the laser printer is typically very expensive both to purchase and to maintain.

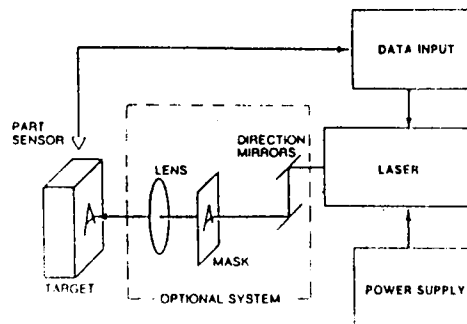


Figure II-6. LASER Printing Technique
Source: NELSON, #34-23

Ink Jet printing (Figure II-7) has been used for years in the beverage industry. It is fast, quiet, and relatively inaccurate. As the name implies, a stream of ink particles are projected from a nozzle through a electrical charging tunnel. The charged particles are then deflected by a magnetic field generated by two parallel deflection plates which properly orient the stream of ink particles on the print medium surface. This method of printing is inexact and for that reason not really well suited to the printing of bar codes--but has been used where other printing techniques are not really feasible (e.g., printing on the side of corrugated boxes).

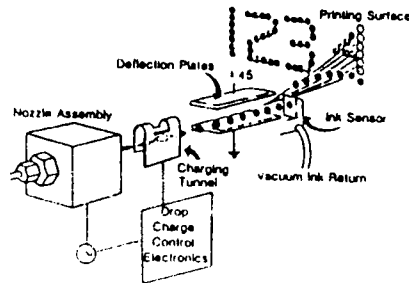


Figure II-7. Ink Jet Printing Technique
Source: NELSON, #34-22

The use of the phototypesetter is another technology that has recently been employed to print bar codes. The phototypesetter technology is the same as that used in the modern newspaper/magazine industry. The technique is based on a computer controlled camera that photographs images as they are displayed on an ultra-high resolution cathode ray tube (CRT) screen. Similar to the electrostatic printers, various fonts (in this case software fonts that are designed to excite certain pixels on the screen) are available for most phototypesetters. The phototypesetter is capable of producing bar codes of exceptionally high quality in terms of bar edge definition, but the size and type of media (i.e., resin-coated photographic paper) may be unacceptable for some applications. For example, this media cannot be read by an infrared probe. The cost of a phototypesetter ranges from a very basic \$16,000 model, to an extremely elaborate and much faster \$500,000 model.

Table II-1 is offered as a comparison of some of the inherent design characteristics of the eleven printing techniques just discussed.

Table II-1. Comparison of Printing Techniques

Printer	Speed	Flexi- bility	Maximum Code Quality	Purchase	Operate
Dot Matrix	30-50/min	High	Low/Low	Low	Low
Square Matrix	30-50/min	High	Low/Med	Low	Low
Formed Font/ Impact	40-100/min	Low	High/High	Med	Med
Thermal	10-20/min	Med	Med/Med	Med	High
Thermal Transfer	10-20/min	Med	Med/Med	Med	Low
Laser	2000/min	Low	Low/High	Very High	Med
Electro- static	200-300/min	High	Med/High	Med	Low
Ink Jet	2000/min	High	Low/Very Low	High	Med
Wet Ink	10-30/min	Low	Low/Low	Low	High
Hot Stamp	100/min	Low	High/Med	Med	High
Photo- typesetter	3-20/min	High	Med/High	Very High	High

Throughout this discussion of various printing techniques, the statement that certain methods yield a higher quality output was made or at least insinuated several times. A definition of print quality and how it is measured, however, has not been offered or provided. One author suggests that "the print mechanism, the media (or substrate), and the ink together determine the quality of the printed symbol" [HARMON, ADAMS, #24-51]. Kathleen Parsons, Vice-President of Sales and Marketing of a leading supplier of bar code verification equipment, emphasizes the importance of print quality as she says:

If a symbol scans only after numerous time--wasting tries, or worse, decodes [SIC] a symbol improperly, the advantages of bar code are reduced or lost. If the scanner can't decode a symbol, the total system disintegrates.

[PARSONS, #35-12]

The measurement of print quality, however, is usually couched in terms of three characteristics.

1. Static Indices
2. Durability
3. User Forgiveness/Tolerance of Angle and Speed Variations

Each of these three characteristics has a significant impact on the First Read Rate (FRR) and/or Substitution Error Rate (SER), and therefore on the success or failure of the system.

The first vital characteristic to be examined is the category of "static indices" of which there are three to be examined. These are:

1. Bar Edge Definition
2. Absolute and Relative Bar Dimensions, and
3. Print Contrast Signal (PCS)

Bar edge definition, also called vertical edge definition, pertains to the uniformity of bar width. Ideally, the horizontal width of each bar or space in a code should not vary regardless of the vertical point at which the measurement is taken. The concept of spots and voids is closely related to that of bar edge definition, for a well-defined bar edge is typically associated with few spots/voids, and a label with numerous spots/voids is usually indicative of poor edge definition as well. The photographs in Figure II-8 may help to

illustrate this point. These 30 times actual size photographs are of labels printed with three different printing techniques.

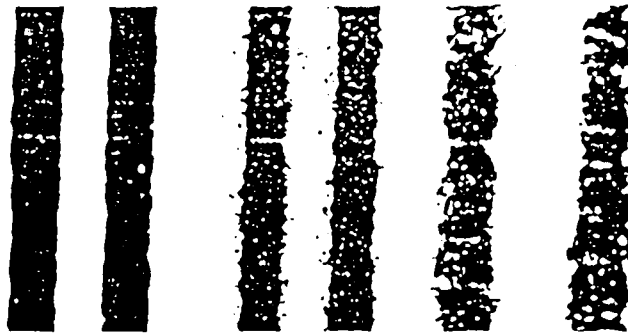


Figure II-8. Comparison of Print Quality
Source: WEILAND, #45-33

The first photo on the left is of a thermally printed label, the second (middle) is of an electrostatically printed label, and the third (right) is of a label printed with a dot matrix printer. These three methods utilize approximately 200, 300, and 160 dots per inch respectively. Clearly the bar edge definition is worst and the number of spots/voids is highest on the dot matrix generated label, and the best characteristics are evident on the thermal label.

Absolute and relative bar/space dimensions are the next important characteristic of printed media to be addressed. Absolute bar/space dimensions are the sole determinant of code density. Only briefly mentioned heretofore, code density is an important factor in the selection of appropriate reading equipment and can play an important role in the selection of print media and printing hardware as well. For instance, a 1 x 1 inch label could not be used to identify a part which requires a 10 character code 39 identifier.

Similar to many of the other symbologies, code 39 is typically printed in three standard densities. High density (9.4 characters per inch), medium density (5.4 cpi) and low density (3.2cpi). With standard high density code 39, the width of the narrow bar or space (often called the nominal width or X dimension of the code) is approximately 7.5 mils. In comparison, the average thickness of a human hair is approximately 8 mils. (Note: 1 mil = 1/1000 inches). A ten character code printed in high density Code 39 requires a minimum horizontal label length of 1.78 inches (1.07 inches for the 10 characters, 0.21 inches for the special start and stop characters, and 0.25 inches of white quiet zone on each end). It is easy, therefore, to understand that the accurate printing of high density code is simply not possible with many printers and/or printing techniques.

The term "Relative bar width" pertains to the ratio of the wide to narrow elements of a code. For most codes, as is the case for code 39, the wide bars/spaces are merely multiples (in width) of the narrow bars/spaces. For codes that utilize only 2 element widths, the ratio is usually specified within an acceptable range. Some codes, however, such as Codabar employ as many as 18 unique bar widths that are not even multiples of one another.

The wide to nominal element width ratio for code 39 must fall within the range of 2.25/1.0 to 3.0/1.0. Thus high density code 39 (i.e., 9.4 cpi) is only truly achieved with a nominal bar width of 7.5 mils and a wide bar width of 16.9 mils (i.e., a ratio of 2.25/1.0).

Here again, a readable bar code depends on strict adherence to these rather tight printing specifications.

The Print Contrast Signal, hereafter referred to as the PCS, is the last static index of print quality to be examined. In simple terms, the PCS is measure of the difference in reflectivity between the bars and the spaces. Clearly, if the photo-optical receiver is not able to distinguish between the amount of light reflected from the bars and the spaces, then a breakdown occurs in the very basis upon which the concept of bar coding is founded.

The usefulness of PCS as an index of print quality, however, is found in its ability to objectively and quantifiably compare the reflective characteristics of a symbol. The formula for calculating PCS is as follows:

$$PCS = \frac{R_L - R_D}{R_L} \times 100\%$$

where R_L = The reflectivity of the spaces or light areas, and

R_D = The reflectivity of the bars or dark areas.

A PCS of greater than or equal to 70% is considered good. Of course, there are a number combinations of black and white reflectivities that will yield a PCS of 70% or better, but a recommended minimum background (i.e., space) reflectivity is 70%. With this minimum 70% space reflectivity, a bar reflectivity of less than or equal to 21% must be achieved to ensure a PCS above 70%.

Each of these three static indices of print quality (i.e., Bar Edge Definition, Absolute/Relative Bar Width, and PCS) may be definitively measured in several ways. Edge definition and bar width may be empirically measured under a microscope, but this is a long and tedious process which is impractical for measuring more than just a few bars. Another approach involves the use of a projection optical comparator, but this method too is time-consuming and labor intensive.

Not until the mid 1970's were electro-optical verification devices available on the market. These devices, such as the RJS (model 3600) that is used extensively in modern industrial applications are one of two types. The first utilizes a laser light source to illuminate, scan, and measure both the reflectivity and width of each bar and space in a symbol many times within 1-2 seconds. The advantages of this type of verifier include its ability to indicate an estimated percentage of successful reads (i.e., an estimated FRR), and this type of verifier does not require physical contact with the print medium. The other type of electro optical verification equipment is one which employs a nonlaser light source. Unlike the laser verifier, this device does require physical contact with the print medium but it can measure widths more precisely (within one ten-thousandth inch---.0001" precision) and it can measure reflectivity of either visible or infrared wavelengths (the laser cannot measure infrared reflectance).

While poor bar edge definition will certainly impact the measured values of both bar width and PCS, a quantitative value is not usually associated with this variable. Rather, visual inspection of a

symbol--either under a microscope or with the naked eye--result in a judgement call of "good or bad, acceptable or unacceptable" based on the perpendicularity of the bar edges and the evidence of spots and voids. The other two static indices of print quality, however, are measurable and quantifiable.

Durability is the next characteristic of print quality to be addressed. In this context, durability is defined as the ability to maintain original print quality. Clearly, even the highest quality label is not of much use if it cannot maintain its high degree of quality throughout its intended lifespan. To a large extent, durability is a result of the environmental factors such as heat, radiation, chemicals (discussed in more detail under the Environmental/Human Factors section of this chapter) but to a lesser extent, the number of times that a label is scanned may contribute to the maintenance of print quality/durability of a label. There are however, several methods to protect a symbol from harsh environments and/or multiple scannings.

The simplest method to augment the durability of a symbol is to use a more stable and resistant media such as mylar instead of paper. This approach is certainly appropriate in situations where external abrasives are prevalent and paper labels are often ripped or torn. Another approach, that will be examined in greater detail later in this chapter is the application of a translucent overlamine. Some experts suggest that:

In applications where the symbol will be exposed to adverse environments such as dirt, grease, temperature extremes, and weather, or the label will be scanned at least 50 times by contact devices, the symbol should be protected with a transparent coating.

[HARMON, ADAMS, #24-46]

The last characteristic of print quality is one that is less frequently mentioned than the others. It is the characteristic of user forgiveness or tolerance of angle and speed variations. While some might argue that this characteristic is a function of the reader's electro-optics or decode algorithm more so than print quality, no definitive studies been made to support this assertion.

Anyone with experience in using a bar code system, however, will confirm that some coded symbols seem to "read better" when scanned more slowly while others yield better results when scanned more quickly. It is also known (and has been documented) that certain wand angles produce better results than others, where wand angle is defined as the tangential angle between the apex of the contact probe and the surface of the printed media. The extent to which these factors versus the quality of the printed media impact bar code system performance is assessed experimentally in Chapters III and IV.

2. Bar Code Readers

There are many types of scanning devices (or readers) in use for collecting source data. These scanners come in many shapes and sizes ranging from the very large stationary processing systems to portable hand held units.

[SOBCZAK, #44-35]

Basically, bar code scanners or readers can be classified in two broad categories--stationary or portable. As the name might suggest, stationary readers are positioned in a fixed location where they

typically have a hard-wired or modem communication connection and an alternating current (AC) power hook-up. Stationary readers may be further subdivided into three additional categories--fixed beam, moving beam, or slot scanners.

Fixed beam readers are those which employ a helium-neon LASER (Light Amplification by Stimulated Emission of Radiation) to emit a steady beam of visible light. To be read/decoded, a bar code must be passed in front of the beam in such a manner that the beam traverses the entire length of the code. While limited in its number of useful applications (i.e., it is primarily used on a fixed assembly line or conveyor system to sort packages), the fixed beam stationary scanner has the greatest depth of field of all scanner types.

Really just a subset of the stationary fixed beam reader with a very short depth-of-field, the slot scanner is popular for some limited applications such as reading employee badges, but it is inflexible and thus impractical for many applications. Similar to the magnetic stripe technology, this method of reading requires that a bar code be mounted on a stiff card that is moved through a narrow slot past a stationary light source. The advantage of this type reader is the great reduction in opportunity for human error, for the movement of the code relative to the reader is regulated by the tight dimensions of the slot.

The moving beam stationary scanner is one of three types. It may be a stationary reader with a contact probe/wand, or it may employ the laser technology in two different manners. In most cases, however, the moving beam scanner, unlike the fixed beam scanner, requires significant human intervention.

The stationary contact probe scanner is the least expensive and most widely used bar code scanner available today. The decoder is typically a pencil shaped device that is connected to a stationary box which controls the communication with a host computer, power, and usually has either a light or speaker to indicate a successful "read." The connection/communication with the host computer is typically via an RS-232C or RS-422 serial interface, but some readers (called wedge readers) are connected in-line between a keyboard and terminal or personal computer. Within the pencil-shaped decoder (some decoders are also pistol shaped) is a single light emitting diode (LED) which may be either a visible (630-700 nanometer wavelength) or infrared (900 nanometer wavelength) light source, and a photo diode light detector. These components are shown below in Figure II-9.

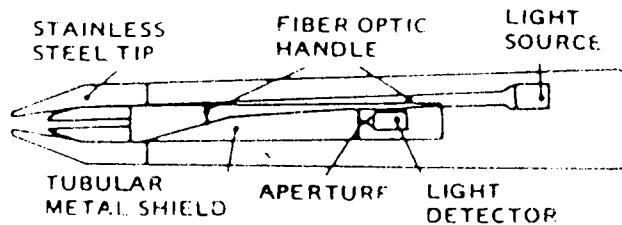


Figure II-9. Schematic of the Contact Probe Scanner
Source: SOBCZAK, #44-36

Light is emitted from the tip of the wand via a fiber optic bundle and either reflected (by the spaces) or absorbed (by the bars) of a bar code. The reflected light reenters the wand through the same aperture, is detected by the photo diode, and creates an analog optical signal.

As previously indicated, moving beam stationary scanners may also employ the laser technology. There are, however, two completely different modes of stationary laser operation. The first mode is the hand-held single line laser scanner that is similar in many respects to the contact probe. In this case, a hand-held "gun type" device (in fact, they are often called laser guns) is connected to a stationary box that controls communication, power, and audible or visual feedback to denote a "good" read. The laser scanner, however, does not require physical contact with the media; in fact, most laser guns have a depth of field from about 3-15 inches. Unlike the fixed beam laser the moving beam projects a single column of light that is swept across a preset linear path by a rotating mirror at a rate of 400-1000 sweeps per minute.

The last type of stationary moving beam scanner to be discussed is the omnidirectional laser. Like the single-line laser, the multiple line omnidirectional laser uses only one laser light source, but unlike the single-line version, it uses a series of rotating mirrors to produce a cross-hatched effect, as shown in Figure II-10. The goal of the omnidirectional laser scanner is, of course, to read a bar code without the requirement of aligning the bars perpendicular to any single laser line.

It is this very expensive type scanner that is used by most supermarkets to expedite the check-out process by relieving the cashiers from having to orient the packages in any specified direction. The other most common use of the omnidirectional scanner is for order

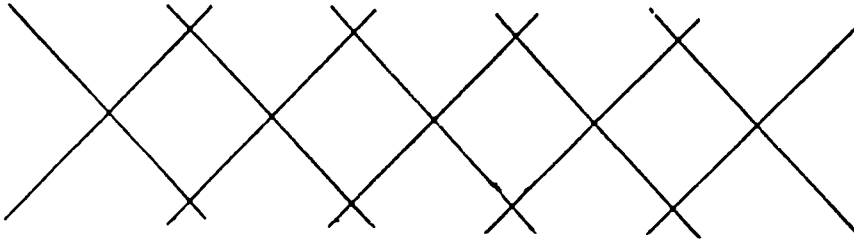


Figure II-10. Omnidirectional Laser Scan Pattern
Source: KAHL, #30-26

picking systems. For example, in 1981, J. C. Penney introduced the omnidirectional scanning technique at each of its six Catalog Distribution Centers and has since realized tremendous savings. In a similar manner, Eastern Airlines has introduced omnidirectional scanning into its baggage handling operations in the Miami International Airport.

The other major category of bar code reading equipment is the portable reader. While the single-line laser and contact probe technologies already discussed are identical for stationary and portable readers, the latter has several other obvious distinguishing characteristics. As the name implies, the portable reader is a lightweight, direct current (DC) powered, movable decoder. Most portable readers include rechargeable nickel-cadmium (NI-CAD) batteries, a nonvolatile random access memory (RAM), and an RS-232 or RS-422 serial communication interface. Some portable units, however, have the capability to communicate via radio frequency (RF) transmission to a host computer. Portable units are designed for the application in which it is impractical to bring the product to the reader. The most common example is

the periodic inventory of a warehouse which stores numerous or large items that are either individually identified by bar code or are on shelves that are identified by bar code. In cases such as these, it is much easier to take the reader to the product.

Figure II-11 graphically depicts the categorized breakdown of bar code readers that has just been discussed.

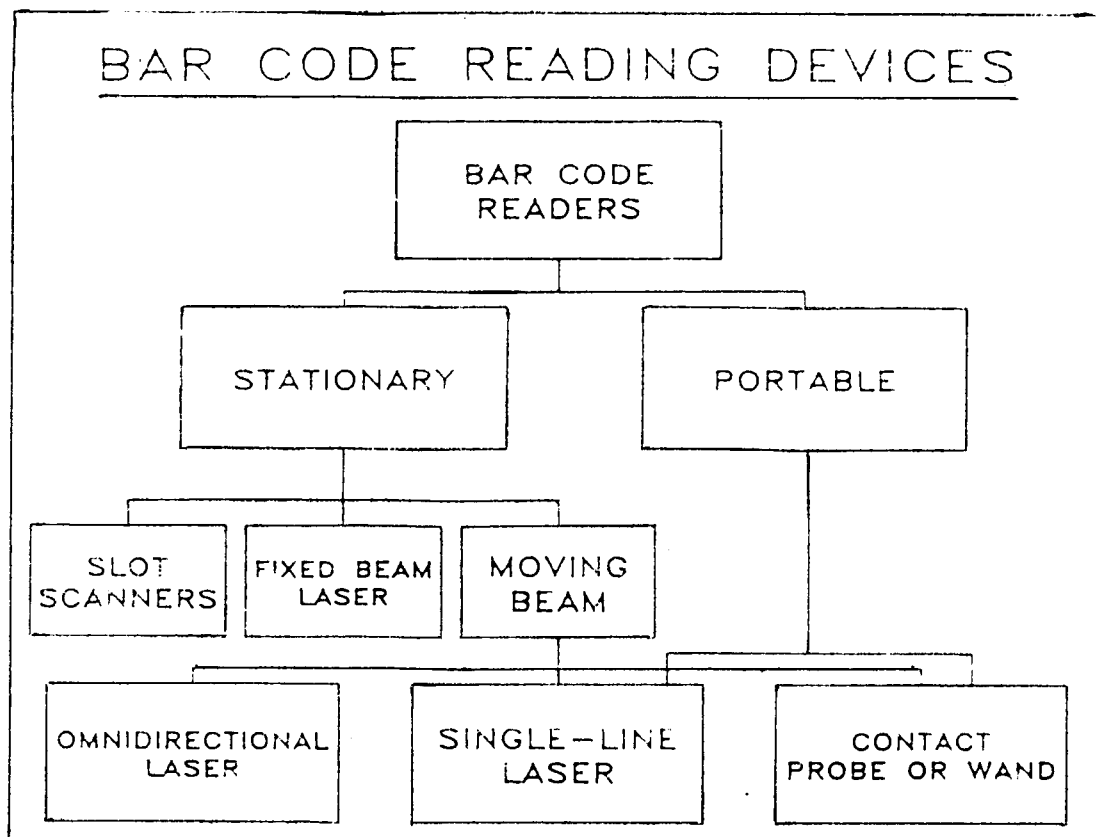


Figure II-11. Bar Code Reader Hierarchy

Regardless of the type of physical configuration and electro-optics used in a scanner, there are two other major components of

any bar code reader which complete the function of decoding a symbol. These are signal conditioning and digital processing.

Signal conditioning is the process by which the analog optical signal is converted into a square wave. This process is also called wave shaping or digitizing, and its purpose is simply to transform an imperfect analog waveform (as shown in Figure II-12 below) into a perfect square wave that consists of binary highs and lows (or ones and zeros) only. This square wave effectively ignores the transition from black to white or white to black or reduces the time of the transition to zero--an effect which could never be achieved in reality even with a perfectly printed bar code.

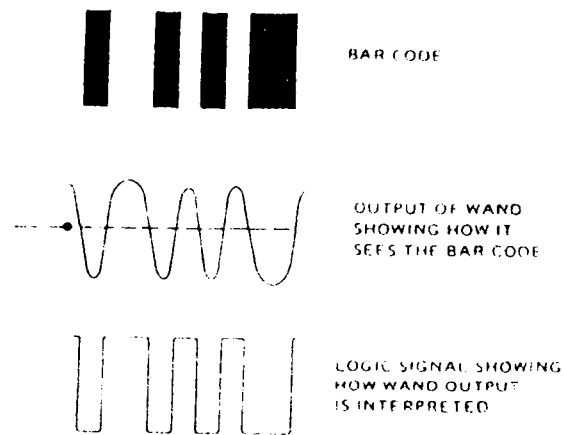


Figure II-12. Bar Code Signal Conditioning
Source: SOBCZAK, #44-38

The quality of the analog wave form and subsequently the square or digitized wave form is proportional to the quality of the printed media. Spots or voids in the bar code symbol can complicate the wave-shaping process, as evidenced in Figure II-13. If a contact probe, for

instance, is passed over a void in a wide bar, the resulting analog signal could be misinterpreted as a narrow bar followed by a wide space by a tolerant or forgiving signal conditioning algorithm. Most often, however, dramatic spots or voids result in the inability to read a bar code (i.e., a no decode) rather than a substitution error or misread.

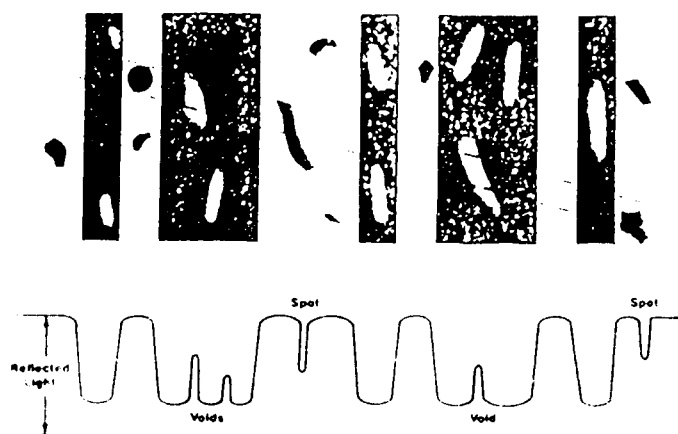


Figure II-13. Bar Code Printing Defects
Source: HARMON, ADAMS, #24-53

Clearly, however, there is a trade-off between a forgiving digitizing algorithm which might misinterpret small media defects but achieves a near 100% first read rate and a conservative digitizer that renders too many "no-decodes" on slightly imperfect media but never yields a substitution error.

It is quite possible to write an algorithm which maximizes FRR [First Read Rate] at the expense of the SER [Substitution Error Rate]. While this might make a system look good at first blush, there would be a bitter price to pay in terms of "true" performance.

[BURKE, #11-39]

The digitized output of the signal conditioner is then used by the last leg or element of the bar code reader--the digital processor. The

digital processor is simply the algorithm that converts the binary pattern, which hopefully corresponds to the pattern of black and white bars, into the appropriate series of digits and characters. This algorithm is, of course, contingent upon the symbology used and a digital processor designed to decode 3 of 9 cannot be successfully used with Interleaved 2 of 5, codabar, UPC or any other code. Some more advanced readers, however, are able to decode more than one symbology by storing more than one digital processor in memory, automatically identifying the symbology (usually by the START and STOP characters), and "rolling-in" the appropriate algorithm. This capability which has been especially popular in receiving applications where incoming shipments may be marked with various symbologies is known as autodiscrimination. In addition to decoding the digitized signal, many digital processors also perform error checking functions as well.

In summary the bar code reader or scanner may be physically configured in several different ways. It may be portable or stationary; it may employ a contact probe or laser scanner. The three major components of any bar code reader, however, are constant and could, in fact, be considered as "standard equipment" for a bar code reader.

1. The electro optics--used to project and collect the light reflected from the media in the form of an analog wave;
2. The signal conditioner--used to shape the analog waveform into a recognizable binary digital pattern; and
3. The digital processor--used to decode and validate the coded binary pattern into characters in an ASCII or some other standard format.

The choice of the ideal bar code reader for a particular application, therefore, depends on several factors: the physical positioning, orientation, and accessibility of the media; the specific symbology and density to be used; the relative importance of data accuracy versus first read rate; the quantity/volume of data to be collected; and, of course, the cost of the reader.

3. Other Bar Code Hardware

Thus far, the two major hardware components of any bar code system have been briefly explored. While they don't warrant a detailed examination, there are other pieces of bar code related hardware which should not be omitted altogether. At a minimum, these include:

1. a port concentrator,
2. a verification device, and
3. a host computer.

A port concentrator is really just a "dumb" multiplexor. The typical bar code port concentrator can handle up to eight individual readers, has some minimal buffering capability, and costs approximately \$3-5000.

A bar code verification device is used to quantitatively measure certain physical characteristics of a bar code label to determine if the code is in conformance with predetermined specifications. A currently popular bar code verifier is the RJS model 3600 which costs approximately \$5000 with a printer and uses two light sources simultaneously to measure virtually every significant parameter of a bar code.

While it should go without saying, no bar code system is complete without a host computer to combine, massage, refine, and report on the data that are decoded and collected by the bar code readers. A host computer is also frequently used to provide both data and electronic operating instructions to a bar code printer.

These last two tasks, however, are not possible without one other key ingredient of a bar code system--Software.

C. Software

This area [the software] of implementing a bar code system is too frequently passed off with the comments, "and the computer takes the data and updates the database and . . . and . . . and . . ." Obviously the computer can, will, and indeed must, do all of these things. But a computer can only do what it is told to do by software. Software can be expensive and, in the case of bar code systems, is the deciding factor in determining the implementation schedule.

[STULTZ, #48-1]

The software associated with a bar code system is multi-faceted. The functions of any bar code system that require software typically include programs to:

1. Drive a bar code printer
2. Prompt an operator to scan an appropriate symbol
3. Poll fixed readers tied to a port concentrator
4. Decode a digital signal
5. Perform error checking on a decoded message
6. Transmit data from a reader to a host computer
7. Edit/validate the content of collected data
8. Store/Retrieve/Manipulate collected data after uploading to the mainframe or other host

9. Integrate bar code data with data collected via other methods
10. Generate batch reports which include data collected via bar code readers
11. Maintain History and Error files

While many of these software modules may be written in high-level, user-friendly languages such as BASIC, C, Pascal, FORTRAN, or PL/1, others require detailed assembler coding, and still others may require a new unique language designed especially for use with a certain vendor's hardware. An example of this last category is the Interactive Reader Language (IRL) that was developed by Intermec, Inc. to program their portable readers.

Unlike some other bar code system parameters (e.g., hardware), software is typically very reliable--after it is verified--and operates very consistently and predictably. Software also, however, is generally easier to change than other system components. While this fact certainly offers some advantages such as the flexibility to adjust and incorporate expanded applications, or the ability to easily accommodate a new operating system (O/S), ill-defined user/system requirements can extend the process of software development and maintenance by unacceptably long periods of time.

In the design of a bar code system, therefore, it is important to consider the following before any software is designed or written:

1. How well are the user's/application's functional requirements defined?
2. What are the special language requirements (if any) of the hardware selected?

3. What special utility and data communication software might be required?
4. What mechanisms are in place to manage configuration/change control?
5. Are the proper resources available to both develop and maintain the software?

D. Environmental/Human Factors

In addition to the hardware and software associated with a bar code system, the last major element concerns environmental/human factors. These factors apply in a broad sense to aspects of both the environment in which a system must operate and the people who must operate the system within that environment.

While the design of a system for some applications, such as the identification of library books, may involve relatively few environmental considerations, environmental conditions may be a paramount concern in the development of other industrial applications.

The tire industry requires labels that can withstand the vulcanizing process. The primary metals industry requires a label that can be applied to an ingot or roll several hundred degrees in temperature, withstand various reheat processes, and resist weathering. . . . The automobile industry needed an adhesive that could be applied and remain on an oily part. The blood industry required an adhesive for blood bags that would withstand freezing and thawing, as well as a label stock that was resistant to blood and urine.

[HARMON, ADAMS, #24-57]

As a further example, the tracking of metal parts through a manufacturing facility may involve such environmental factors' as:

extreme high or low temperatures, contact with various chemicals and solvents, exposure to strong electromagnetic radiation (e.g., ultraviolet light), abrasive handling, salt or coolant sprays, water and chemical baths, high humidity, high/low pressures. The impact of these and other extreme environmental conditions on both the bar code equipment and media as well as the humans that must use that equipment are important considerations--especially in the selection of equipment and the physical location/placement of the media.

As an example, it might be possible and desirable to design a removable traveler to identify parts that must undergo a series of heat treating operations. On the other hand, if serialized part accountability is of utmost importance, then heat-resistant, metal bar code tags may accompany the parts throughout their demanding routings. A less extreme example is one in which a fixture is used to hold a part for a nondestructive X-ray test of a weld joint. An adhesive thermal label may not be appropriate for identification of either the part or the fixture in this example, for X-rays as well as other radiation sources can drastically impair the readability of a thermally printed label.

Another pertinent environmental consideration is the anticipated number of times that a label will be scanned (especially by a contact probe reader). While an anodized aluminum tag with a rough surface might be detrimental to the delicate tip of a contact probe, the more common problem involves the marring or destruction of the surface of an inked paper label by a contact probe. A common solution to this problem employs the use of a clear plastic overlamine. This approach

may, however, be expensive--especially for on-site printing techniques--and may even add additional problems in the event that bubbles or wrinkles are left as a result of improper application of the over-laminate. Also, some seemingly translucent laminates are, in fact, infrared-opaque and may not be used in conjunction with a reader that uses an infrared light source.

In extremely harsh environments, there is really but one recourse for ensuring continued system operation--the use of permanent or semi-permanent symbols.

The first step in selecting a "permanent" bar code label stock is to define the concept of "permanency." To be considered permanent, a bar code label must survive its service environment--and still fulfill true, accurate reading requirements.

[HAZY, #25-74]

For some applications, permanency may mean short term survival under exceptionally severe conditions; for others, it may mean extended survival under moderately harsh conditions. While the selection of a particular medium to be used in any harsh environment is, of course, contingent on the application specific requirements, the choice of a permanent bar code tag is really very limited. There are, in fact, only three principle methods of producing permanent bar code labels--all three of which are based on the use of anodized aluminum.

The first method, is simply an etching process in which an anodized black layer of dye is etched or burned (with a laser) away from the surface of an aluminum base--exposing the more reflective surface of raw aluminum. While laser etching may be used to produce high

density codes with superior bar edge definition, the cost of this technique is relatively high (up to \$1.50 per tag) and laser etched tags cannot be read with a contact probe. The second "permanent" method of bar code production involves the application of anodically formed oxide coatings on the surface of aluminum (or possibly steel) in conjunction with an overcoat of clear epoxy, ceramic, or paint. While less expensive and somewhat faster than the other two techniques, this method produces media that is still subject to surface abrasion and cannot be used to create high density codes. The third technique for producing "permanent" bar code media is used to accommodate the worst-case environments. This technique, known as the photographic image embedment process, employs silver compounds rather than dyes in the pores of the anodic layer. The silver based substances are then exposed--much like a photograph--to provide the required light and dark contrast of a bar code. Advantages of this method include ultra high resistance to temperature, solvents, dirt, and moisture; excellent bar edge definition; and a smooth surface that will accommodate both contact and noncontact probes/readers. Disadvantages include the cost per tag and relatively slow throughput/production rates.

Of at least tantamount importance to the environmental factors associated with the design of a bar code system are the human factors.

As we explore emerging technologies for manufacturing applications, whether CIM, CAD/CAM, or robotics, lets not overlook a still--and for the foreseeable future- vital component of the total manufacturing system: the human being.

[DUTTON, #16-4]

Or as another author puts it:

There are two aspects to planning for the implementation of CIM--technical and organizational. The technical aspects are quantifiable and generally known in advance. The organizational aspects are not quantifiable and are generally ignored in advance.

[WELTER, #52-19]

In this explanation, the author uses the term organizational aspects to refer to the "human factors." He goes on to say, "We have focused on the 'tool' and have, for the most part, ignored how the worker will use the tool" [WELTER, #52-18].

The important human factors aspects of designing a bar code system can be classified in one of two categories: the physiological and the psychological. The physiological factors are related to anthropomorphic considerations of bar code reader station design, the formatting of individual bar code labels or large menus of bar code labels (often called bar boards), and the design of individual pieces of bar code hardware (e.g., the weight of a portable reader). The psychological factors pertain to a worker's perception of the system's impact on his/her workplace. In recent years, much has been written on this subject about the attitudinal effects of automation, the potential for worker morale problems, and the need for adequate training and education. Not even the best designed bar code system can survive the malicious destruction of users that see the system as a threat and refuse to either make it or allow it to work as intended. George Coletta of Westinghouse Electric, Inc. suggests that the best method of assuring user acceptance of a bar code system is to get the users involved as

early as possible in the conceptual planning and development of the system. His implication is that an end-user is more likely to accept and even promote the system if he feels that he had a hand in the development of the system--or was a responsible participant and not simply imposed upon by an outsider.

Thus, the critical factors of a bar code system--hardware, software, and environmental/human--factors have been defined. And an insinuation that the proper treatment/design considerations for each of these three factors would result in an effective, successful system has been made. How, however, is the success of a bar code system measured? What are the indices of success?

E. Bar Code System Critical Success Factors

While user-friendliness and user acceptance are often proposed as indices of success, these are subjective in nature and not easily quantifiable. A more tangible index of a system's success is its return-on-investment or ROI. This index, however, is a high-level measure that is very contingent on the specific application and the amount of change in the associated business practices or methods. For example, a productivity improvement project could involve the use of bar coding to automate data collection as only one portion of a much larger transition from an outdated manual mode of operation that depends on a robotically controlled automatic storage and retrieval system that is tied to a shop floor order entry system. The point is that ROI is a good objective measure of total system success, but the total system

success may or may not truly reflect or be indicative of the success of the bar code portions of the system.

There are, however, two indices of success that are frequently associated with a bar code system and are truly a measure of the success achieved as a direct result of the selection/design of a system's bar code hardware, software, and environmental/human factors. While mentioned previously in the discussion of bar code printers and readers, these two measures of success are equally contingent on the other system factors as well. These indices are:

1. FRR (First Read Rate), and
2. SER (Substitution Error Rate)

The accepted definition of FRR is "the ratio of the number of times in which a good read occurs on the first try, divided by the number of attempts" [HARMON, ADAMS, #24-15]. Similarly the SER is defined as "the ratio of the number of invalid or incorrect characters entered into the database to the number of valid characters entered" [HARMON, ADAMS, #24-240]. Each of the hardware, software and human/environmental related parameters of a system's design has both an individual and synergistic (when evaluated in conjunction with other parameters) impact on the total system's success. The impact of each can be measured in terms of FRR and SER.

All of the system parameters heretofore discussed, however, fall into one of two distinct categories--GO/NOGO parameters and Level-of-Success parameters. As the name might suggest, GO/NOGO parameters are those that affect not the practicality of a bar code system but

rather the practicability. In other words, the specification of a particular GO/NOGO parameter will not impact how well a system works--but rather whether a system will work at all. Some examples of GO/NOGO parameters include:

1. the environmental impact on label/media material or composition;
2. the software used to collect the data or to move/upload data from a reader to a host computer;
3. the compatibility between the specified reader and symbology.

In each of these and other cases, the system will either work or not--there is no real middle ground. For instance, readers designed to be used in a supermarket to decode UPC can not be used with the Code 39 symbology. Generally speaking, the impact of these GO/NOGO parameters is independent of other system parameters (i.e., the synergistic impact of parameters in this category is irrelevant). That is not, however, the case for those parameters that fall in the other category.

Level of success parameters of a bar code system are those that don't generally (except in extreme conditions) dictate whether a system works, but rather how well a system works. Frequently, the impact on FRR and SER that results from the combined contribution of parameters in this category is greater than the sum of the contributions of the individual parameters (i.e., the synergistic effect). Many important contributors to a system's level of success have been discussed; a few of these are:

1. the reader's decode algorithm;
2. operator training and experience;

3. the print quality of the labels/media

Some would suggest that it is this last level of success parameter (print quality) that has perhaps the greatest individual impact on the FRR, SER, and subsequently success or failure of a bar code system. This assertion is, at least, supported by a number of experts in the field of bar coding. In a recent publication, one of the largest bar code equipment vendors Hewlett-Packard, Inc., states that:

The media selected to support the bar code symbol and the printing system used to deposit the ink (bars) onto this media are the most critical elements in the design of a bar code system because of the large systematic and random errors which may be introduced into the system.

[Hewlett Packard, #27-17]

Another author bluntly states that "the print quality of a bar code label is critical to the success of the bar code system" [BAR CODE NEWS, #10-6]. He goes on to suggest that:

people can read poorly printed text. Why shouldn't scanners read poorly printed bar code? The answer is, people can reconstruct lost data from context. Scanning systems cannot. Poor bar code print quality results in low first-read rate, low data accuracy, and low user happiness.

[BAR CODE NEWS, #10-6]

Bruce Wray, Director of Marketing for Computype Inc.--a large bar code label manufacturer, says it perhaps best of all as he states:

Our experience with hundreds of scanning systems all over the world, spans more than a decade, and our conclusion is this: the single biggest problem in scanning systems is the bar code labels. . . . It is ironic that sophisticated scanning systems costing hundreds of thousands of dollars are brought to an abrupt halt by a label that costs only pennies The quality of the bar code image is the single most important factor determining the success of a scanning system.

[WRAY, #57-30]

Others, however, can argue just as convincingly that there is no single factor but rather a combination of the many factors discussed

herein that contribute to a high/low FRR and thereby impact the success/failure of a bar code system. The experiment outlined in the following chapter is, therefore, designed to measure the impact of several of these factors on a bar code system in order to evaluate statistically the relative significance of each.

CHAPTER III

AN EXPERIMENT TO ASSESS THE IMPACT OF
THREE BAR CODE SYSTEM PARAMETERS

A. Experimental Design and Procedure

1. Purpose/Objective

The intent of this experiment is to analyze the impact of three variables on the success/failure of a bar code system. The measure of success/failure to be used is the First Read Rate (FRR) percentage as defined previously in Chapter II. The three variables are:

1. Print Technique (4 types will be tested)
2. Operator (2 operators will be randomly selected)
3. Application (3 label lengths will be utilized)

The FRR of every possible combination of these three variables (24 treatment conditions) will be measured as described herein, and analysis of variance (ANOVA) techniques will be employed to determine which, if any, of the variables or combination of variables have a statistically significant impact on the success or failure of the bar code system. The results of this experiment should then allow one to characterize the impact of printer, application/label length, and operator on FRR and to predict FRR based on a predetermined combination of these three variables. Additionally, this experiment should allow one to either confirm or disprove the assertion of many "experts" that the printed media or print quality is the single most important factor in deciding the fate of a bar code system.

2. Equipment and Materials

For the purpose of this experiment, the following equipment and materials will be used as described in the Procedure section:

a. Bar Code Reader:

An Intermec Model 9300 reader with an Intermec Model 1260 Handheld, Visible-Light, Contact Probe

b. Bar Code Printers:

While this experimental procedure could certainly be applied to any or all the printing techniques discussed in Chapter II, the following four (4) were selected on the basis of current popularity, availability of media, and on the fact that they are representative of the various dissimilar techniques of printing available today.

P1: An IMTEC 2035 High-Density Impact Printer

P2: An Intermec 8625 Thermal Printer

P3: A Fujitsu DPL-24 Dot Matrix Printer

P4: An Autologic APS--Micro5G Phototypesetter

c. Operators:

The two operators, who volunteered their time to make this experiment possible, were selected at random from a pool of 35 Martin Marietta employees. This pool of 35 employees represents the Computer Integrated Manufacturing staff at the Martin Marietta Energy Systems Division Y-12 Plant in Oak Ridge, Tennessee. While it is true that the average technical knowledge of these employees pertinent to bar coding and bar

code systems probably exceeds that of most other populations, it is also true that the actual hands-on experience of this group with bar coding equipment is not especially significant. For this reason, it is assumed that the limited population, from which the experimental operators were chosen, does not significantly bias the results. The names of the two selected operators are:

1. T. L. Payne
2. R. J. Bittner

The BASIC program that was prepared to randomly select these participants and results of its execution may be found in appendix B.

d. Labels:

While there are certainly numerous distinct bar code applications in existence today, one of the most significant distinguishing factors for any application is the quantity of data encoded in a label--which corresponds directly to label length. For the purposes of this experiment, three different label lengths of five (5), ten (10), and fifteen (15) characters will be employed. Ten labels of each length will be printed on each of the four aforementioned printers as shown in Figure III-1.

Label #	5-Character Label	10-Character Label	15-Character Label
1	123AB	123AB123AB	123AB123AB123AB
2	B123A	B123AB123A	B123AB123AB123A
3	AB123	AB123AB123	AB123AB123AB123
4	3AB12	3AB123AB12	3AB123AB123AB12
5	23AB1	23AB123AB1	23AB123AB123AB1
6	XYZ89	XYZ89XYZ89	XYZ89XYZ89XYZ89
7	9XYZ8	9XYZ89XYZ8	9XYZ89XYZ89XYZ8
8	89XYZ	89XYZ89XYZ	89XYZ89XYZ89XYZ
9	Z89XY	Z89XYZ89XY	Z89XYZ89XYZ89XY
10	YZ89X	YZ89XYZ89X	YZ89XYZ89XYZ89X

Figure III-1. Experimental Label Content

It is important to note that the ten (10) and fifteen (15) character labels contain the same information that is found in the corresponding five (5) character label. The information is merely repeated two (2) and three (3) times respectively for the longer labels. The intent of specifying the label content in this manner is to ensure that no factors other than label length (i.e., the desired factor) are introduced as possible causes of variation in the FRR.

3. Procedure

As noted previously, there are 24 possible unique combinations of the three experimental variables (operator, printer, and application). For each of these unique combinations, two independent experimental trials were run--generating a total of 48 FRR data points. To avoid biasing the results, the order in which these trials were performed was completely randomized using a BASIC program as shown in appendix B. For each trial, the operator was presented with a stack of ten (10)

Hollerith Field cards (i.e., IBM punched cards) with one bar code label attached to each card. The ten cards were randomly ordered/shuffled prior to each experimental trial. The operator was then asked to scan each card in the deck one (1) time and then to repeat the exercise (i.e., rescan each of the ten cards) nine (9) more times--for a total of 100 attempted label readings with the Intermec bar code reader.

During this process, each operator was carefully observed and the number of missed reads was recorded. The First Read Rate (FRR) was then easily determined as the quotient of successful or good reads to total attempted reads times 100%. Since each trial in this experiment consisted of 100 attempted reads, the FRR is more simply equivalent to the number of good or successful reads. The FRR data for all 48 trials were then recorded in tabular form and ANOVA techniques were used to analyze the data.

4. Assumptions

1. The BASIC routines utilized both to select the operators and to order the 48 experimental trials generated truly random output;
2. The sample labels are representative of typical labels generated with the specified printing techniques;
3. The label content (i.e., characters encoded) does not significantly impact the results of the experiment (i.e., ABC123 is not significantly different from LMN567 or any other combination of standard alpha-numeric characters);

4. The sequence of cards/labels within a group of ten (10) is not a significant experimental factor;
5. No degradation of the FRR is realized as a result of the repeated use of either the reader/wand (which is used for a total of 4800 experimental reads) or the sample labels (which are used for a total of 40 attempted reads each).

B. Experimental Results

The following two charts are a matrix representation of the experiment just described. Figure III-2 is intended to show the random order in which the 48 experimental trials were performed. For example, the two trials involving Operator-01, Printer-P4, and Application/Label Length-A5 were performed as experimental trial numbers 14 and 45; and the first experimental trial performed was with Operator-02, Printer-P2, and Application/Label Length-A15. The BASIC program used to generate this random sequence may be found in appendix B.

Figure III-3 is simply a tabulated version of the actual First Read Rate (FRR) data collected for each of the 48 experimental trials. An analysis of this data is presented in the following chapter.

	Operator 1			Operator 2		
	5-Char Label	10-Char Label	15-Char Label	5-Char Label	10-Char Label	15-Char Label
High-Density Impact Printer (P1)	Trial 1	25	6	4	12	8
	Trial 2	29	22	26	20	18
Thermal Printer (P2)	Trial 1	7	35	2	30	1
	Trial 2	37	40	38	44	17
Dot-Matrix Printer (P3)	Trial 1	5	3	32	16	10
	Trial 2	31	13	34	28	33
Photo- Typesetter (P4)	Trial 1	14	15	19	42	24
	Trial 2	45	48	21	46	41

Figure III-2. Randomized Experimental Trial Numbers

	Operator 1			Operator 2		
	5-Char Label	10-Char Label	15-Char Label	5-Char Label	10-Char Label	15-Char Label
High-Density Impact Printer (P1)	Trial 1	88	88	81	92	88
	Trial 2	90	90	81	88	91
Thermal Printer (P2)	Trial 1	99	91	67	100	94
	Trial 2	100	94	91	99	95
Dot-Matrix Printer (P3)	Trial 1	94	80	88	99	96
	Trial 2	96	81	84	100	95
Photo- Typesetter (P4)	Trial 1	92	46	5	99	94
	Trial 2	94	84	42	97	88

Figure III-3. Experimental FRR Data

CHAPTER IV

ANALYSIS OF RESULTS

A. General Observations and Comments

1. Although the two operators were not allowed to watch each other perform the experiment, they did speak to each other during the experiment which was conducted over a period of several days, and a spirit of competition between the two was apparent.
2. The majority of the data was collected during two 4-hour periods of 8-12 a.m. on two consecutive weekdays. The experimental conditions during these two periods were effectively identical.
3. No one card/label in the sequence of 10 was repeatedly missed. In other words, the first or last card in a series were not missed significantly more often than the 4th or 7th in the series of ten (10) cards/labels.
4. In general, the experiment was somewhat monotonous, repetitious, and boring for the operators and this factor may have had a slightly negative impact on the FRR results. In total 4800 attempted reads/scans were made and 4212 were successful for an experimental FRR of 87.75%.

B. Characteristics of the Experimental Variables

1. Print Technique

- a. The four printers used were:
 - (1) An IMTEC 2035 High Density Impact Printer
 - (2) An Intermec 8625 Thermal Printer
 - (3) A Fujitsu DPL-24 Dot Matrix Printer
 - (4) An Autologic APS-Micro5G Phototypesetter
- b. All four printers were in good operating condition; none of the four is more than three years old.
- c. The media printed on each of the four printers is believed to be a good representation of typical media printed on each particular type of equipment.

2. Operators

- a. Both operators are relatively good athletes with good hand eye coordination.
- b. Both operators had a tendency to bear down too hard on the media with the wand.
- c. Both operators have completed levels of formal education of more than four years of collegiate work and have attained Baccalaureate degrees or more.
- d. Neither operator has had extensive practice or significant experience with the use of bar coding equipment.
- e. Both operators were willing participants in the experiment.

- f. Operator-01--had some difficulty with the physically larger (lower density codes). In particular, it seems that he had trouble adjusting his speed properly.
- g. Operator-02--was able to quickly establish a rhythm which allowed him to be more fluid with hand motions and thus achieve on average a higher FRR (i.e., better performance).

3. Application

- a. Ten samples for each of three different label lengths of 5, 10, and 15 characters were printed on each of the four printers. These 120 labels were then applied (via peel-off backing or transparent tape) to standard hollerith field cards.
- b. Due to the nature of the printers themselves (and some parameters set by the experimenter), the physical size and density of the label types varied as shown in Figure IV-1.

C. Data Trends and Evidence of Learning

Figure IV-2 depicts the performance of the two operators over the course of the experiment. The twenty-four (24) data points represent the difference in FRR (i.e., improvement or learning) between trials-T1 and T2 at each of the 12 treatment conditions for each of the two operators. Negative values indicate a poorer performance on trial-T2 at a particular treatment condition.

Label Printer	Label Length	Avg. Label Density Char./Inch*	Avg. Label Dimensions (Inches)	H X W
IMTEC 2035	5 Char	9.43 characters/inch	0.41 "	x 0.75 "
	10 Char		0.41 "	x 1.25 "
	15 Char		0.41 "	x 1.81 "
Intermec 8625	5 Char	6.42 characters/inch	0.75 "	x 1.09 "
	10 Char		0.75 "	x 1.88 "
	15 Char		0.75 "	x 2.63 "
Fujitsu DPL-24	5 Char	6.94 characters/inch	0.44 "	x 1.00 "
	10 Char		0.44 "	x 1.75 "
	15 Char		0.44 "	x 2.44 "
Autologic APS-Micro-5G	5 Char	3.02 characters/inch	0.53 "	x 2.31 "
	10 Char		0.53 "	x 4.00 "
	15 Char		0.53 "	x 5.63 "

*As measured with an RJS model 8600 bar code verification device (see Chapter II for explanation).

Figure IV-1. Characteristics of the Printed Media

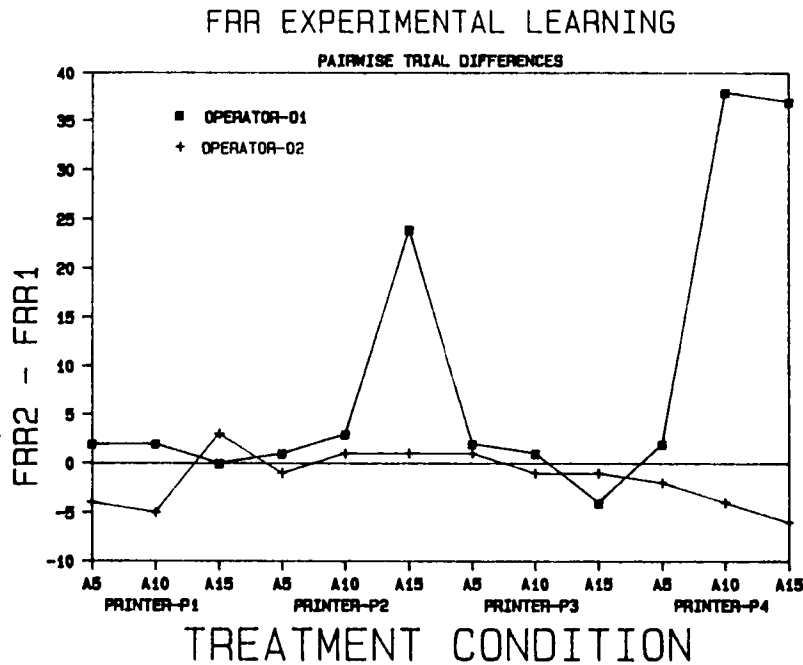


Figure IV-2. Experimental Learning

In order to determine whether a significant amount of learning occurred between trials-T1 and T2, a paired t-test was performed. In this test, the data displayed above in figure IV-2 (i.e., the FRR for trial-T1 at a given treatment condition minus the FRR for trial-T2 at the same treatment condition) was utilized.

In the event that no learning occurred, the value of each of these 24 points should be zero (0). Thus, a t-test of the hypothesis that the mean of these FRR differences equals zero (0) was performed, and some surprising results were realized. At a 0.05 level of significance (L.O.S.), the hypothesis could not be rejected--indicating that no significant learning occurred between trials 1 and 2. In fact, the mean

difference between trials-T1 and T2 was calculated to be 3.75% with a standard error of 2.41%--yielding a confidence interval of approximately [-1.1 to 8.5] at the 0.05 L.O.S. (i.e., $3.75 \pm t^*(2.4)$). Thus, one can be 95% confident that the learning effect is somewhere between -1.1% and 8.5%.

Closer examination of the data reveals that the hypothesis can not be rejected even at a 10% L.O.S. This is true in part because operator-02 actually showed a decrease in performance (i.e., the opposite of learning) from trial-T1 when his average FRR was 95.16% to trial-T2 when his mean FRR fell slightly to 93.66%. While this decrease in performance was certainly not expected, it is perhaps explained by the monotony of the experiment. In other words, it is possible that operator-02 simply became bored with the experiment and that his lowered level of concentration made itself manifest in a lower FRR. Operator-01, on the other hand, showed a slight increase in FRR for trial-T2 as he improved from 76.6% to 85.6%.

At any rate, the fact that there is no significant difference between trials-T1 and T2 allows for the simplification of the linear model (discussed in the following section) by removing trial number from consideration as a potentially significant effect on FRR in the analysis of variance procedure. The elimination of trial number as a significant effect in the model, in turn, allows for the incorporation of all other two and three way interactions in the model by providing additional degrees of freedom for the experimental error term.

D. The Linear Model--ANOVA

In general, this type of experiment may be classified as a balanced, mixed effects, factorial ANOVA experiment with three independent variables or factors. The dependent/response variable is First Read Rate (FRR), and the independent/treatment variables or classes are printer (fixed), operator (random), and application/label length (fixed). The mathematical model for this experiment can be written as:

$$FRR_{i,j,k} = M + T_{i,j,k} + E_{i,j,k}$$

where

M = the overall experimental FRR mean

$T_{i,j,k}$ = the 24 treatment effects

$$= P_i + O_j + A_k + PO_{i,j} + PA_{i,k} + AO_{j,k} + POA_{i,j,k}$$

$E_{i,j,k}$ = the error within each of the 24 treatments

$i = 1, 2, 3, 4$ for the four printers

$j = 1, 2$ for the two operators

$k = 1, 2, 3$ for the three applications/label lengths

This linear model expresses the fact that FRR is characterized by the overall experimental mean, plus or minus any deviation expected as a result of the three main effects (i.e., Printer(P), Operator(O), and Application(A)), plus or minus any deviation expected as a result of the two-way interaction effects (i.e., $P*O$, $P*A$, $O*A$), plus or minus any deviation expected as a result of the single three-way interaction effect (i.e., $P*O*A$).

The Statistical Analysis System (SAS) software package from SAS Institute, Inc. was used to analyze the experimental FRR data and the tabular data shown in Table IV-1 were generated.

Table IV-1. Mixed Effects Model ANOVA Table

Source	DoF	Sum of Squares	F-Value	PR > F
Total:Model	23	11491.00	6.77	0.0001
Within:Error	24	1772.00	1.00	0.5
Corrected Total	47	13263.00	(R-Square = 0.87)	
Between:				
Operator (O)	1	2133.33	28.89	0.0001
App/Lab Length (A)	2	1906.63	1.85	0.3513
Printer (P)	3	1984.50	1.21	0.4390
O * A	2	1032.54	6.99	0.0040
O * P	3	1637.17	7.39	0.0011
A * P	6	1566.38	1.27	0.3885
O * A * P	6	1230.46	2.78	0.0340

Without discussing all of the calculations in detail, it is important to note that the algorithms and formulae used by the SAS software in deriving the above results are those commonly accepted as standards for performing a balanced, mixed-effects analysis of variance procedure. In the above table, for example, the F-values for all of the random effects (i.e., O, O*A, O*P, and O*A*P) are calculated by dividing the Mean Square values between specified treatment conditions or classes by the the Mean Square value of the residual or error term, where the Mean Square value is equivalent to the Sum of Squares (SS) divided by the associated degrees of freedom (DoF), and the SS is calculated as follows:

Total SS = the sum of the squares of the deviations of the individual data points from the grand mean of 87.75;

Error SS = the sum of the squares of the deviations of the data points in each class from the mean of that class summed for all classes, and;

Class SS = the number of items in each class times the sum of the squares of the deviations of the class means from the grand mean of 87.75%.

The denominator used in calculating the F-value ratios for all of the fixed effects (i.e., A, P, and A*P), however, must be adjusted to account for the possibility that one or both of the operators are biased. This "adjustment" involves using the expected Mean Square of the appropriate interaction term instead of the Mean Square Error (MSE) of the residuals as the denominator in the F-ratio quotient. While alternatives to this method of accommodating random effects certainly exist (e.g., the Hotelling T^2 test which is quite involved or the Imhoff approximation which employs the regular F-statistic with an adjusted number of degrees of freedom), the SAS software makes convenient provision for the former method by allowing the programmer to specify the appropriate denominator terms for the analysis as shown in Table IV-2.

Table IV-2. Revised F-Test Ratios

Source	Revised F-Test Denominator
P	O*P
A	O*A
A*P	O*A*P
All Others	Unchanged (i.e., MSE)

Also of interest is the R-Square value associated with this model. The R-Square value, which is a measure of how much variation in the dependent variable (i.e., FRR) can be accounted for by the model, is generally indicative of how well the model fits the data. For this model, a value of 0.87 (which is simply the ratio of the Model Sum of Squares to the Corrected Total Sum of Squares) implies a reasonably good fit.

The right-most column in the Table IV-1 which is labeled "PR > F" indicates the probability that the experimental F-statistic will be greater than the calculated F-Value assuming that the null hypothesis is true (i.e., that there is no significant difference between specified treatment conditions or that the specified treatment condition has no significant effect on FRR). This value (often referred to as the P-value) is, of course, simply equivalent to the traditional alpha value or level of significance for the calculated F-value with its associated degrees of freedom. For example, the tabular data would indicate that an F-value for source (O) of 28.89 with 1 and 24 degrees of freedom would be significant at an alpha level of 0.0001. In other words, at the more typical alpha level of 0.05, a much smaller F ratio would be expected--indicating that the null hypothesis (that there is no significant difference between the two operators) should be rejected. In the event that more than two operators had been used in the experiment, however, this test would not indicate which of the operators is/are significantly different from the others.

Closer examination of the ANOVA table reveals the fact that all of the effects involving "operator" (and none of those not involving

operator) are significant at the 0.05 level of significance--as evidenced by the fact that the "PR > F" column contains only values less than 0.05 for O, O*A, O*P, and O*A*P. There is, in fact, an argument which suggests that once a high order interaction effect (e.g., O*A*P) has been identified as significant, then continued testing for lower order effects may be invalid because the higher order interaction is likely to impact the lower order effects. Using this philosophy, an analyst would stop at this point and attempt to explain the cause and significance of the three-way interaction of Operator-Printer-Application on FRR. A closer examination of the raw data, however, reveals that the significance of this three way interaction effect is attributable in large part to two seemingly anomalous data points--which represent the performance of Operator-01 with Printer-P4 on Applications-A10 and A15.

These results are not really all that surprising, however, for during the experiment, it was obvious that operator-01 had a significant amount of difficulty with the physically longer, lower density labels produced on the phototypesetter (Printer-P4). A reasonable theory is that his primary problem was one of speed. This conjecture explains his atypical performance by assuming that because the labels produced on the phototypesetter were so much longer, operator-01 tended to slow down in order to make sure that the wand tip stayed within the boundaries of the bar code, but by doing so, he passed the minimum speed threshold at which the reader is capable of decoding.

Although operator-02 did not share in this problem with the physically longer labels, it is doubtful that this problem is unique only

to operator-01. In other words, since both operators were selected randomly from a larger (and hopefully unbiased, typical) population, it is likely that some percentage of the global population would also experience this inability to read long, low density, phototypeset bar codes at a reasonable or acceptable FRR. And although operator-01 did show significant improvement in his ability to read these codes from trial-T1 to trial-T2, he was reading the codes under the somewhat atypical experimental conditions of 100 scans at a time. In actual practice, it is unlikely that an operator would be required to read 100 labels consecutively. Thus, improvement due to learning is likely to occur even more slowly under actual working conditions. It is also important to note, however, that operator-01 was given no coaching on how to improve his method once the experiment was begun, and it is possible (if not likely) that some minimum amount of additional instruction or training could significantly improve this operator's performance, because (as demonstrated by operator-02), the printer-P4 labels can be read with a much higher FRR.

Because it is not practical to meaningfully portray this three-way interaction on two dimensional paper, only the two-way interactions (i.e., O*A, and O*P) are presented in Figure IV-3 in an attempt to graphically depict the disparity between operators, and especially the impact of the two specific questionable data points on the overall experimental results.

In these two graphs, the fact that the two performance lines of operators-01 and 02 are not close together or overlying one another is

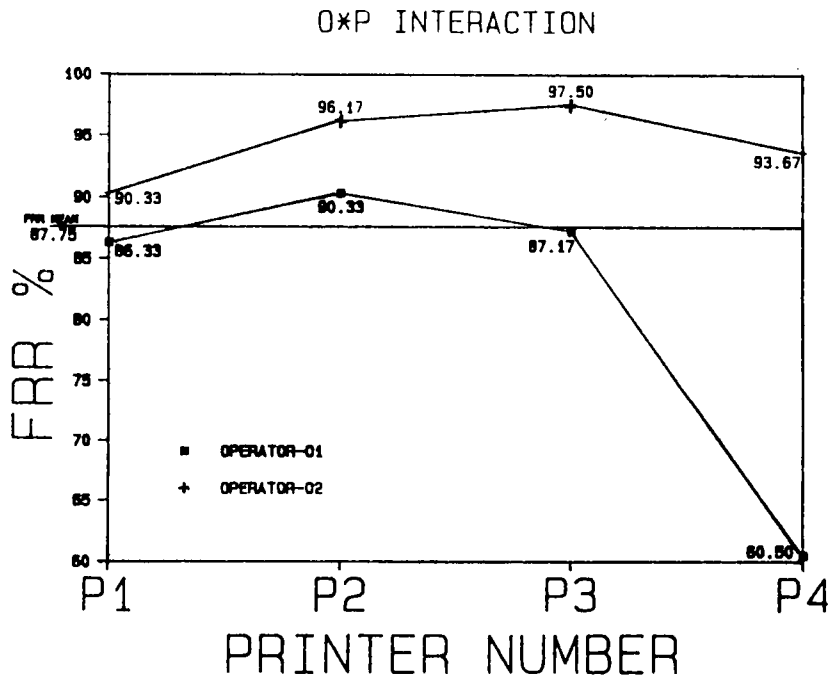
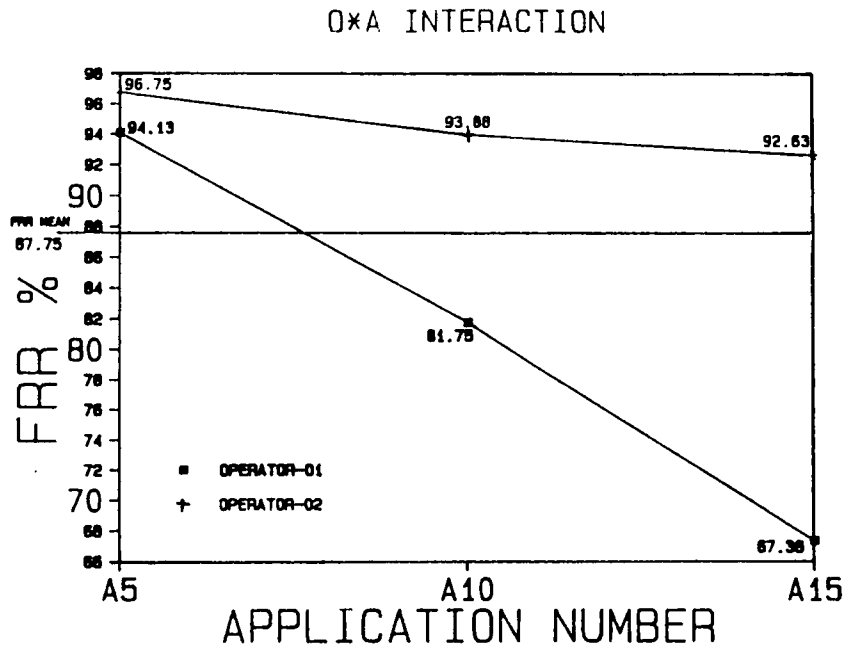


Figure IV-3. O*A and O*P Two-Way Interactions.

attributable to the significant operator effect; the fact that the two lines are not parallel is indicative of the two-way interaction effects. Thus, these graphs support that which is suggested by the ANOVA table (Table IV-1, p. 74).

Because, however, only two operators were used in the experiment, and because the complex three-way interaction could be thought to mask or camouflage some significant main effect differences among printers and/or applications, an analyst might, at this point, be tempted to abandon the initial experimental design and to perform separate analyses on the data generated by each of the two operators. In fact, if this approach is pursued, the results and conclusions are considerably different.

Using this method, the linear model would be revised as follows:

$$FRR_{i,j,k} = M + P_i + A_j + T_k + PA_{i,j} + E_{i,j,k}$$

where

$FRR_{i,j,k}$ = the dependent First Read Rate, and

M = the overall experimental mean for 1 operator

P_i = the 4 printer main effects for 1 operator

A_j = the 3 application/label length effects for 1 operator

T_k = the 2 trial number effects for 1 operator

$PA_{i,j}$ = the two-way interaction effects between printer and application/label length for 1 operator

$E_{i,j,k}$ = the residual error within each of the treatments for 1 operator

When this model is applied for each operator, the following ANOVA tables, Tables IV-3 and IV-4, are generated:

Table IV-3. Operator-01 ANOVA Table

Source	DoF	Sum of Squares	F-Value	PR > F
Total:Model	12	9553.83	7.12	0.0014
Within:Error	11	1230.00	1.00	0.5
Corrected Total	23	10783.83	(R-Square = 0.88)	
Between:				
App/Lab Length (A)	2	2867.58	12.82	0.0013
Printer (P)	3	3442.83	10.26	0.0016
Trial Number (T)	1	486.00	4.35	0.0612
A * P	6	2757.42	4.11	0.0207

Table IV-4. Operator-02 ANOVA Table

Source	DoF	Sum of Squares	F-Value	PR > F
Total:Model	12	303.33	6.54	0.0020
Within:Error	11	42.50	1.00	0.5
Corrected Total	23	345.83	(R-Square = 0.88)	
Between:				
App/Lab Length (A)	2	71.58	9.26	0.0044
Printer (P)	3	178.83	15.43	0.0003
Trial Number (T)	1	13.50	3.49	0.0884
A * P	6	39.42	1.70	0.2108

As evidenced in these two tables--and as shown previously--the effect of trial number (T) proves not to be significant for either operator at the 0.05 level of significance (L.O.S.). For operator-01, however, all of the other measured effects are significant at the 0.05 L.O.S.

Figure IV-4 graphically depicts the performance of operator-01 for each of the three application label lengths and for each of the four printers.

The use of J.W. Tukey's studentized range test on on these two main effects (i.e., Application and Printer) confirms that which is suggested by the graphs--for operator-01, there is (at the 0.05 L.O.S.) a significant difference among each of the three Application/Label Lengths, but with respect to printers, only printer-P4 is significantly different from the others. Similarly, pairwise t-tests for all 12 unique combinations of the 4 printers and the 3 application/label lengths support the previous assertion that only two of these combinations are significantly different--both from each other and from all the other combinations. These two are the last two entries in Table IV-5; they are Printer-P4 with Application-A10 (with a mean FRR of 65.0) and Printer-P4 with Application-A15 (with a mean FRR of 23.5).

When the revised linear model is used in a similar fashion to analyze the data generated by operator-02, somewhat different results are achieved. As depicted in Table IV-4, only the main effects (i.e., Printer and Application/Label Length) are significant at the 0.05 of L.O.S. for operator-02. Unlike operator-01, but as expected due to his more consistent performance, there is no significant interaction between Application and Printer for operator-02.

The application of pairwise t-tests to the data generated by operator-02 reveals that his performance with labels created on printer-P2 was not significantly different (again, at the 0.05 L.O.S.) from that

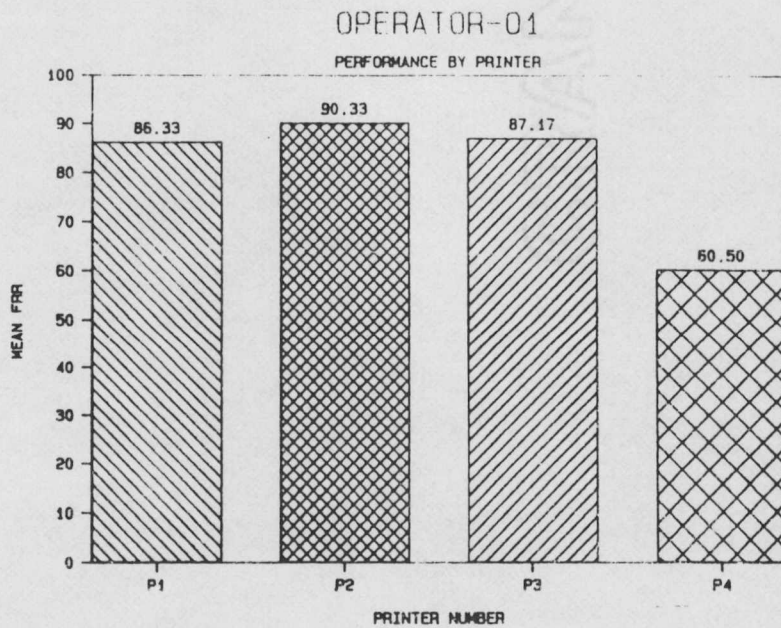
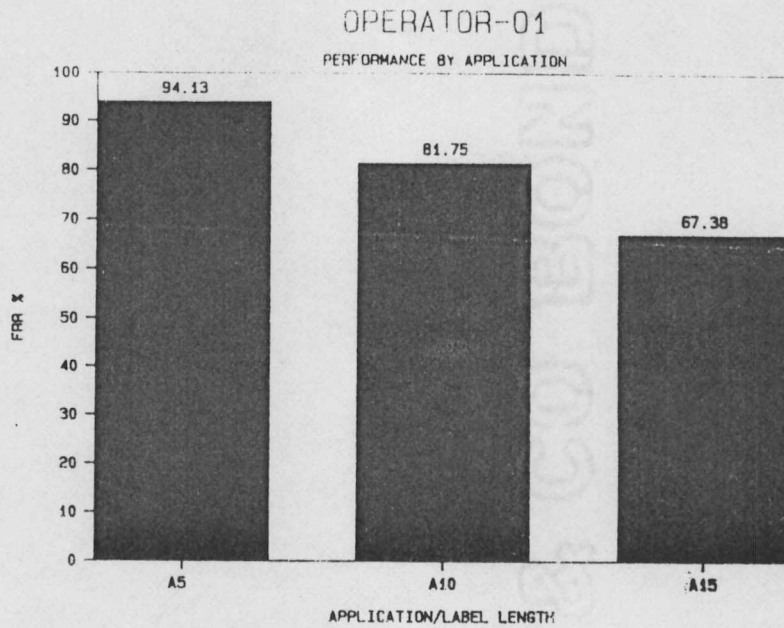


Figure IV-4. Operator-01 Performance by Application and Printer

Table IV-5. Operator-01 A*P Two-Way Interaction Table

Combination	Printer	Application	Mean FRR
1	P1	A5	89.0%
2	P1	A1	89.0%
3	P1	A1	81.0%
4	P2	A5	99.5%
5	P2	A1	92.5%
6	P2	A1	79.0%
7	P3	A5	95.0%
8	P3	A1	80.5%
9	P3	A1	86.0%
10	P4	A5	93.0%
11	P4	A1	65.0%
12	P4	A1	23.5%

with labels printed on printer-P3, but that these two means are significantly different from those associated with printers-P1 and P4 (which are also different from each other). Similar t-tests reveal that the First Read Rates associated with applications-A10 and A15 (independent of or averaged across all printers) are not significantly different, but that the difference between these two and the mean for application-A5 is statistically significant.

Thus, the use of the approach in which the data for each operator is analyzed independently would lead one to the conclusion that the main effects of Printer and Application each have a significant and independent impact on FRR.

The fact remains, however, that two operators were used in the execution of this experiment, and this fact may not be ignored. Even if printer-P4 is excluded altogether from the analysis (thereby eliminating the few seemingly anomalous data points and the significance of the

three-way interaction), then the printer and application main effects are still not significant. In fact, as evidenced by Table IV-6, the exclusion of printer-P4 from the analysis renders the operator effect (and only the operator effect) significant.

Table IV-6. Mixed Effects Model ANOVA Table Without Printer-P4

Source	DoF	Sum of Squares	F-Value	PR > F
Total:Model	17	1422.14	4.49	0.0014
Within:Error	18	335.50	1.00	0.5
Corrected Total	35	1757.64	(R-Square = 0.81)	
Between:				
Operator (O)	1	406.69	21.82	0.0002
App/Lab Length (A)	2	370.89	2.82	0.2618
Printer (P)	2	164.06	2.57	0.2798
O * A	2	131.56	3.53	0.0509
O * P	2	63.72	1.71	0.2091
A * P	4	163.94	1.35	0.3886
O * A * P	4	121.28	1.63	0.2109

Thus, it appears that the significant two-way and three-way interaction effects are primarily attributable to the atypically poor performance of operator-O1 on printer-P4, but that the significant difference between the two operators is not entirely explained by these few outlying data points. In any event, there are no apparent assignable causes that would allow for the exclusion of these points from the analysis. But even if there were, the results would be basically the same--a significant operator effect on FRR and no significant printer or application/label length effects.

CHAPTER V

SUMMARY AND CONCLUSIONS

A. Experimental Conclusions

The experiment documented in the two previous chapters reveals some interesting facts about the impact of the three parameters tested on the FRR of a bar code system. First, if the experiment had been run with only one operator, then as expected, one could conclude that shorter label lengths result in measurably better FRR's and that the use of different print techniques could also be expected to have a significant impact on the FRR of a bar code system (as suggested by the "experts"). The fact, however, that two operators were used to perform the experiment reveals that any differences among printers or application/label lengths are likely to be overshadowed by greater or more significant differences among operators. In other words the experiment does not suggest that there are no differences among printers or applications, but rather that the effects of the operator (both independently and in conjunction with a specified printer and/or label length) may be expected to have the greatest impact on FRR and therefore on the overall success of the bar code system.

Secondly, based upon the results of this experiment, one can predict that--regardless of which of the four print techniques is chosen and regardless of which of the three label lengths is selected, the FRR for 95% of all operators will fall somewhere within the interval from 54.2% to 100%. Please note that the limits of the 95% confidence

interval with a mean of 87.75% and a standard deviation of 16.8% are actually 54.2% and 121.4%, but clearly an FRR of greater than 100% can never actually be realized. This large confidence interval, which is based on the performance of only two operators, would, of course, be better if more operators had been used in the experiment, but because the operators were randomly selected, it is theoretically applicable to any operator selected from a similar population.

Thirdly, the conclusions of this experiment strongly suggest that the focus for ensuring a successful bar code system should be first and foremost on the operator. Several possibilities include :

1. Further experimentation to identify the particular successful and/or unsuccessful characteristics of an operator's scanning technique;
2. Further experimentation to assess the impact of operator training on FRR performance;
3. Exploration of fully or partially automated methods of bar code scanning to reduce or eliminate any dependence on the necessarily inconsistent human operator (e.g., the use of laser scanners as discussed in Chapter II).

By discounting the widely held view that print quality is THE most important or critical bar code system parameter, however, this experiment, fourthly and perhaps most importantly, suggests that additional, more detailed experimentation is yet required in order to truly characterize all of the intricate parameters that might possibly impact the manual FRR associated with a bar code system. Some possibilities that

this experiment suggests include the effect of code density on FRR (this parameter was ignored in the experiment) or the two-way interaction effect of code density and label length (i.e., the number of characters in a label). Still other possibilities include the speed at which the label is scanned--clearly there is some minimal acceptable speed--or the tangential angle of approach between the wand and the label surface. And as previously mentioned, more time consuming experimentation would be required in order to adequately characterize the the impact of operator and operator level of training on FRR. Also, duplicate or parallel experimentation would be required to assess the impact of all of these and other parameters on a system's Substitution Error Rate (SER)--the other significant and measurable success index for a bar code system. Thus, while this experiment has both confirmed some long held and intuitively acceptable suspicions of certain bar code system parameters and called others into question, it has perhaps most significantly provided additional food for thought and opportunity for experimentation with other less obvious bar code system parameters.

B. The Future of Bar Coding

1. Trends in Automatic Identification

Early in 1985, Deloitte Haskins, and Sells of Detroit, one of the largest international accounting firms, established an automatic data entry department to meet the needs of manufacturers.

[DOYLE, #14-64]

USA Today, the national daily newspaper, ran a feature story about automatic identification on the first page of the business section.

[BARCODE NEWS, #40-27]

These two recent quotations are an indication of both the perceived present and future popularity and, in fact, importance of automatic identification in the workplace. As discussed in Chapter I, the manifestations of automatic identification are becoming more and more apparent not only in business but also in other aspects of our daily lives. From the grocery check-out line to the bank's automatic tellers, from our new VISA and MasterCard to the processing of our bankdrafts/checks, from auto computers that are trained to recognize our voices to the ultra high-tech and sophisticated vision sensing robots--our lives are being permeated to a greater and greater extent by the expanding technologies of automatic identification. It is, in fact, projected that the bar code market alone will surpass \$1.6 billion in annual sales by next year (1988).

Like many highly technical fields, it is difficult to forecast with any accuracy exactly what the future holds for the field of automatic identification. Current trends, however, would seem to indicate a natural evolution toward lower costs and physical miniaturization. Similar to the currently popular personal computer, much of the newest automatic identification equipment is falling dramatically both in cost and in physical size. With respect to the shrinking physical dimensions, both the A.I. media (e.g., magnetic stripes or bar codes) and the equipment used to read/decode and print the media are affected. In fact the miniaturization of other high-tech equipment has in large part contributed to the miniaturization of A.I. media. For example, the ultra high density bar code was first designed to accommodate the tiny

amount of space available for mounting a label on small printed circuit boards.

In addition to these trends in the traditional AI technologies, significant strides continue to be made in the more sophisticated fields of voice recognition and multi-dimensional vision systems as well. In fact, computers that can both "talk" and "listen" are already available on the market for less than \$10,000.

While these technologies continue to improve, however, the application and usefulness of bar coding continues to grow at a phenomenal rate, and it is this tried and tested technology that many believe will outrun the others and carry modern industry and other businesses into the next century.

2. Trends in Bar Coding

According to Claudia Devaux, bar code program manager for the Manufacturing Systems Group at Hewlett Packard . . . during fiscal 1985, HP sold \$47.5 million in bar code products.

[BARCODE NEWS, #40-27]

While some would argue that bar coding has already become the pre-eminent A.I. technology in existence, there is little disagreement that this technology is at least, becoming the most widespread and accepted technique for automating the identification of materials, food items, capital assets, transportation cargo, and even, in some instances, people.

This assertion is, at least, supported by a number of experts in the field including Barbara Dutton who bluntly states that "only those companies that invest in plant modernization such as this [bar coding]

will be competitive in the long term" [DUTTON, #18-62]. Even computer manufacturers such as Sperry claim that bar code is "today's technology for increased manufacturing productivity" [SPERRY, #47-5].

The technology of bar coding has like most of its high-tech twentieth century peers been subject to a number of significant improvements and advancements. Since October 20, 1949, the day that Norman Woodland and Bernard Silver first applied for a U.S. patent relating to "the art of article classification . . . through the medium of identifying patterns," the field of bar coding has seen many changes.

Similar to other A.I. techniques, the trend in bar coding is toward lower costs and physically smaller equipment and media. Also, as discussed herein, many improvements have been made to provide bar codes that last longer and may be read more reliably with higher first read rates. The experiment documented in the previous chapter, however, reveals the importance that the operator can play in the success of a bar code system. Thus, it is important to recognize that, while an estimated 82% of the bar code readers in use today are handheld contact probes, innovative and affordable techniques and equipment (such as the handheld laser scanner) must continue to be developed or improved in order to offset the necessarily imperfect performance of humans that is required in the operation of most (if not all) bar code systems.

In conclusion, it is apparent that the technology of bar coding is here to stay for at least the foreseeable future. It should also be apparent that a potentially large number of critical factors or parameters (only a few of which have yet been tested) might have a

significant impact on the level of success or failure realized by the implementation of a bar code system. And while significant strides are continually being made in the bar code hardware arena, there is not yet available a guaranteed formula for success--no sure fire combination of hardware, software, and environmental/human factors that can ensure success. Rather, many decisions are left to the system designer. An ever-increasing amount of information is, however, available to make informed decisions relative to the selection of hardware, the development of software, and the definition, establishment or merely accommodation of certain environmental/human factors--for these are the critical parameters that impact the success of a bar code system.

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APPENDICES

APPENDIX A

CODE 39 CHARACTER SET--BAR/SPACE CONFIGURATIONS

CHAR.	PATTERN	BARS	SPACES	CHAR.	PATTERN	BARS	SPACES
M		10001	0100	m		11000	0001
N		01001	0100	n		00101	0001
O		11000	0100	o		10100	0001
P		00101	0100	p		01100	0001
Q		10100	0100	q		00011	0001
R		01100	0100	r		10011	0001
S		00011	0100	s		01011	0001
T		10010	0100	t		00111	0001
U		01010	0100	u		10001	1000
V		00110	0100	v		01001	1000
W		10001	0010	w		11000	1000
X		01001	0010	x		00101	1000
Y		11000	0010	y		10100	1000
Z		00101	0010	z		01100	1000
.		10100	0010	.		00011	1000
SPACE		01100	0010	SPACE		10010	1000
.		00011	0010	.		01010	1000
\$		10010	0010	\$		00110	1110
%		01010	0010	%		00000	1101
		00110	0001			00000	1011
		10001	0001			00000	0111

APPENDIX B

BASIC PROGRAMS

BASIC Program to Randomly Order the 48 Experimental Trials

```
10 REM "This Program is intended to randomly select the order"
20 REM "of the 48 experimental FRR trails to be performed."
30 PRINT
40 PRINT
50 DIM M(48)
60 FOR N =1 TO 48
70 M(N) = 0
80 NEXT N
90 RANDOMIZE TIMER
100 FOR I=1 TO 48
110 K=INT (RND*(49))
115 IF K=0 GOTO 110
120 IF M(K) $ 0 GOTO 110
130 M(K) = I
140 NEXT I
150 FOR J=1 TO 48
160 PRINT "Treatment/Box #";J;"should be performed as trial #";M(J)
170 PRINT
180 NEXT J
190 END
```

Treatment/Box # 1 should be performed as trial # 29
Treatment/Box # 2 should be performed as trial # 22
Treatment/Box # 3 should be performed as trial # 4
Treatment/Box # 4 should be performed as trial # 20
Treatment/Box # 5 should be performed as trial # 43
Treatment/Box # 6 should be performed as trial # 8
Treatment/Box # 7 should be performed as trial # 25
Treatment/Box # 8 should be performed as trial # 6
Treatment/Box # 9 should be performed as trial # 26
Treatment/Box # 10 should be performed as trial # 12
Treatment/Box # 11 should be performed as trial # 47
Treatment/Box # 12 should be performed as trial # 18
Treatment/Box # 13 should be performed as trial # 37
Treatment/Box # 14 should be performed as trial # 40
Treatment/Box # 15 should be performed as trial # 2
Treatment/Box # 16 should be performed as trial # 30
Treatment/Box # 17 should be performed as trial # 11
Treatment/Box # 18 should be performed as trial # 1
Treatment/Box # 19 should be performed as trial # 7
Treatment/Box # 20 should be performed as trial # 35
Treatment/Box # 21 should be performed as trial # 38
Treatment/Box # 22 should be performed as trial # 44
Treatment/Box # 23 should be performed as trial # 27
Treatment/Box # 24 should be performed as trial # 17
Treatment/Box # 25 should be performed as trial # 5

Treatment/Box # 26 should be performed as trial # 13
Treatment/Box # 27 should be performed as trial # 34
Treatment/Box # 28 should be performed as trial # 28
Treatment/Box # 29 should be performed as trial # 9
Treatment/Box # 30 should be performed as trial # 33
Treatment/Box # 31 should be performed as trial # 31
Treatment/Box # 32 should be performed as trial # 3
Treatment/Box # 33 should be performed as trial # 32
Treatment/Box # 34 should be performed as trial # 16
Treatment/Box # 35 should be performed as trial # 39
Treatment/Box # 36 should be performed as trial # 10
Treatment/Box # 37 should be performed as trial # 14
Treatment/Box # 38 should be performed as trial # 48
Treatment/Box # 39 should be performed as trial # 21
Treatment/Box # 40 should be performed as trial # 42
Treatment/Box # 41 should be performed as trial # 23
Treatment/Box # 42 should be performed as trial # 24
Treatment/Box # 43 should be performed as trial # 45
Treatment/Box # 44 should be performed as trial # 15
Treatment/Box # 45 should be performed as trial # 19
Treatment/Box # 46 should be performed as trial # 46
Treatment/Box # 47 should be performed as trial # 36
Treatment/Box # 48 should be performed as trial # 41

BASIC Program to Randomly Select Operators

```
10 REM "This program is intended to randomly select 2 numbers"
20 REM "in the interval from 1 to 35 which correspond to two"
30 REM "employees in the Y-12 Plant CIM Division. These two"
40 REM "operators will be used to perform an FRR experiment"
50 REM "for Paul C. Stumb in support of his Master's Thesis."
60 PRINT
70 PRINT "The following numbers were randomly selected in the "
80 PRINT "interval from 1 to 35."
90 PRINT
100 PRINT
110 DIM X(2), M(2)
120 RANDOMIZE TIMER
130 FOR I=1 TO 2
140 X(I)=RND
150 M(I)=1+(34*X(I))31
160 IF I=1 GOTO 180
170 IF M(I)=M(1) GOTO 140
180 PRINT "Operator Number :";I;"is CIM Employee Number :";M(I)
190 PRINT
200 NEXT I
210 END
```

Results:

The following Numbers were randomly selected in the interval from 1 to 35.

Operator Number : 1 is CIM Employee Number : 26

Operator Number : 2 is CIM Employee Number : 3

CIM PERSONNEL

1. J. H. Akers
2. A. W. Backus
3. R. J. Bittner
4. D. K. Buckner
5. L. M. Cuddy
6. G. L. Dippo
7. J. L. Ewing
8. J. G. Facelli
9. A. K. Farrar
10. D. R. Fletcher
11. V. B. Frazier
12. T. L. Futrell
13. R. Gilreath
14. V. E. Gordon
15. H. A. Harper
16. K. P. Hearn
17. J. D. Heansley
18. E. G. Hess
19. R. E. Hewgley, Jr.
20. D. J. Jones
21. B. L. Littleton
22. C. L. Lovette
23. W. K. McElmurray
24. S. A. McGuire
25. S. M. Murphy, Jr.
26. T. L. Payne
27. D. P. Proffitt
28. P. C. Ray
29. P. C. Stumb
30. G. A. Thomas
31. J. N. Treadwell
32. A. K. VanHull
33. B. W. Williams
34. J. C. Wilson
35. M. R. Cloutier

APPENDIX C

EXPERIMENTAL RAW DATA

TABLE 1. SEQUENCING OF EXPERIMENTAL TRIALS :

		TCT			RJR		
		Operator 1			Operator 2		
		5-Char Label	10-Char Label	15-Char Label	5-Char Label	10-Char Label	15-Char Label
High-Density Impact Printer (P1)	Trial 1	90 1, 29	90 2, 22	81 3, 4	88 4, 20	94 5, 42	88 6, 8
	Trial 2	88 7, 25	88 8, 6	81 9, 26	92 10, 12	89 11, 47	91 12, 18
	Trial 1	100 13, 37	94 14, 40	67 15, 2	100 16, 30	94 17, 11	94 18, 1
	Trial 2	99 19, 7	91 20, 35	91 21, 38	99 22, 44	95 23, 27	95 24, 17
Dot-Matrix Printer (P3)	Trial 1	94 25, 5	81 26, 13	84 27, 34	100 28, 28	98 29, 9	95 30, 33
	Trial 2	96 31, 31	80 32, 3	88 33, 32	99 34, 16	97 35, 39	96 36, 18
	Trial 1	92 37, 14	84 38, 48	42 39, 21	99 40, 42	94 41, 23	94 42, 24
	Trial 2	94 43, 45	46 44, 15	5 45, 19	97 46, 46	90 47, 36	88 48, 41

LEGEND :

Treatment	Exp.
Box	Trial
Number	Number

VITA

Paul Cavert Stumb was born in Nashville, Tennessee on February 8, 1960. He attended the Ensworth Elementary School and Montgomery Bell Academy High School in Nashville before matriculating to Auburn University in the fall of 1978. In the summer of 1982, he was graduated with High Honors from Auburn University with a Bachelor of Industrial Engineering degree.

Soon after accepting full-time employment with Union Carbide Corporation in Oak Ridge, Tennessee, Mr. Stumb enrolled in the evening school program at the University of Tennessee, Knoxville, and began study toward a Master's degree. In June of 1987, he completed the requirements for the Master of Science degree in Industrial Engineering.

Mr. Stumb, a registered Professional Engineer, is a member of Tau Beta Pi, Alpha Pi Mu, Phi Kappa Phi, Sigma Pi Sigma, Pi Mu Epsilon, Omicron Delta Kappa, the Institute of Industrial Engineers (IIE), and the Society of Manufacturing Engineers (SME). He is currently employed as a Systems Engineer at the Martin Marietta Energy Systems Y-12 Plant in Oak Ridge, Tennessee.