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MILITARY HANDBOOK

ENCODERS

SHAFT ANGLE TO DIGITAL

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

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FOREWORD

1. This military handbook is approved for use by all Departments and Agencies of the Department of Defense and supersedes MIL-HDBK-231(AS) dated 1 July 1970.

2. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: Commanding Officer, Naval Air Engineering Center, Engineering Specifications and Standards Department, Code 53, Lakehurst, NJ 08733-5100, by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

3. This handbook provides basic and fundamental information on encoder techniques, terminology, operation, and number systems. It will provide valuable information and guidance to personnel concerned with the preparation of specifications and the procurement of encoders. The handbook is not intended to be referenced in purchase specifications except for informational purposes, nor shall it supersede any specification requirements.

4. An encoder is a device for sensing the rotation or position of a shaft and providing a means for indicating that position. A rudimentary application of the basic encoder concept, which is still widely used today in the maintenance of automobile engines, employs a simple index mark on the flywheel and a fixed reference mark adjacent to the flywheel. Rotation of the flywheel results in movement of the index mark relative to the reference mark and is a function of engine operation and main shaft position. The reference mark and the index mark are placed so that alignment of the two indicates that a selected piston is sitting at top dead center. Another common example of the encoder principle is the familiar automobile speedometer and odometer. This device senses the rotation of the drive shaft of the vehicle, thereby providing the operator with an indication of shaft speed in analog form calibrated in miles per hour (speedometer needle), as well as a digital count of shaft revolutions calibrated in linear miles to an accuracy of 0.1 mile (odometer). In general, any variable which can be represented as a function of the rotation of a shaft (pressure, speed, flow rate, positioning, distance, time, and so on) can be sensed using an encoder and a representative indication or signal can be provided for a broad variety of uses including control, operation, maintenance, and sequencing.

5. The dramatic advancement in weapon systems during World War 11 emphasized the need for rapid and accurate transmission of shaft position data to remote devices. Fire control systems were developed for automatic, high-speed gun laying which required a means for transmitting radar positional data to a remote gun position to aim and fire the weapon. The primary solution was, of necessity, an analog approach using synchro devices Although adequate for the applications of that time, the analog technique has inherent inaccuracies due to deviations from linear input-output characteristics. However, development in this area led to the subsequent development of fast, accurate, and compact digital shaft encoders.

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1. SCOPE

1.1 Scope. This handbook describes the operation of contact and non-contact (formerly brush and brushless) shaft-position, analog-to-digital encoders. It contains physical descriptions and illustrations of encoders, techniques used, theory of operation, background information on binary codes, coding principles and limitation, definitions of encoder terminology, and other criteria for selecting an encoder including identification and marking of encoders for military use.

1.2 Applicability. In many situations, data to be measured can only, or most easily, be extracted in analog form. Since much of the available measurement readout equipment operates on the decimal system (decimal data inputs) , the analog data to be measured must be changed to digital form. Encoders and associated equipment perform this function. This particular handbook is concerned primarily with encoders that receive the input in the form of a change in shaft position. However, many of the principles herein are applicable to all types of encoders.

1.3 Purpose. It is the intent of this handbook to familiarize personnel with encoders and encoder operation so that intelligent choices can be made in system design. It is intended primarily for use by engineers, technically oriented personnel, or management personnel who wish to learn the general background of encoders. As such it is neither all-inclusive nor fundamental-oriented. Knowledge of the contents herein should provide the background for constructive conferences with encoder representatives in solving system design problems.

2. REFERENCED DOCUMENTS

2.1 Government documents.

2.1.1 Specifications, standards, and handbooks. The following specifications, standards, and handbooks form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those listed in the latest issue of the Department of Defense Index of Specifications and Standards (DODISS).

SPECIFICATIONS

MILITARY

MIL-E-4158	- Electronic Equipment Ground; General Specification for
MIL-E-5400	- Electronic Equipment, Aerospace; General Specification for

SPECIFICATIONS (Continued)

MILITARY

MIL-E-16400	Electronic, Interior Communication and Navigation Equipment, Naval Ship and Shore; General Specification for
MIL-E-85082	Encoders, Shaft Angle to Digital; General Specification for

STANDARDS

MILITARY

MIL-STD-202 - Test Methods for Electronic and Electrical Component Parts

MIL-STD-454 - Standard General Requirements for Electronic Equipment

MIL-STD-461 - Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference

MIL-STD-462 - Electromagnetic Interference Characteristics, Measurement of

MIL-STD-810 - Environmental Test Methods and Engineering Guidelines

(Unless otherwise indicated, copies of federal and military specifications, standards, and handbooks are available from the Standardization Documents Order Desk, Bldg. 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.)

2.2 Non-government publication. The following document forms a part of this document to the extent specified herein. Unless otherwise specified, the issues of the documents which are DoD adopted are those listed in the issue of the most recent DODISS.

IEEE-91 - Standard Graphic Symbols for Logic Functions

(Non-Government standards and other publications are normally available from the organizations that prepare or distribute the documents. These documents may also be available in or through libraries or other informational services.)

2.3 Order of precedence. In the event of a conflict between the text of this document and the references cited herein, specification requirements take precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. DEFINITIONS

3.1 Accuracy. The maximum angular difference between the shaft angle input to an encoder and the indicated shaft angle as read from the code output. Accuracy includes both transition error and quantizing error, and is the quantitative statement of the maximum of all errors.

3.2 Ambiguity. Inherent error arising from multiple bit changes in a polystrophic code when going from one digit to an adjacent digit; it can usually be corrected through proper logic design.

3.3 Analog. Pertaining to data in the form of smoothly variable physical quantities.

3.4 AND gate. A logic element or circuit operating such that if all inputs are true (binary 1), the output indicates True; and that if one or more inputs are false (binary 0), the output is False.

3.5 Angular misalignment. The maximum deviation in perpendicularity between the encoder shaft and the face of the mounting surface, and represents the total of shaft misalignment, shaft runout, and mounting face runout measured at the worst respective positions.

3.6 Antiambiguity logic. Prevents ambiguous outputs from encoders using polystrophic codes.

3.7 Arithmetic unit. That portion of a computing system which performs arithmetic operations.

3.8 Autocorrelation. The process of checking an encoder for drop-out errors which utilizes a comparison between stored encoder data and actual encoder output.

3.9 Autocorrelator. A test unit for determining encoder reliability by comparing successive samples and registering an error whenever the difference between two consecutive samples is more than one.

3.10 Axial load, maximum. The maximum axial force that may be applied in either direction without affecting encoder performance.

3.11 Axis, crystalline cube. The assignment of one and zero values to the end points of the 12 lines that define the geometrical cube structure such that any axis under discussion may be defined by a three-coordinate system.

3.12 Binary. The term referring to the number 2 or to the number system with a radix of 2.

3.13 Binary code. The definition of a series of binary numbers relative to the corresponding number system represented. (For a particular code, refer to the index and referenced text.)

3.14 Binary coded decimal (BCD). A decimal notation in which the individual decimal digits are each represented by a group of binary bits. Usually associated with codes of four or more bits used to define the Arabic numbers 0 through 9.

3.15 Binary number. A mathematical system in which only two digits are used (1, O).

3.16 Biquinary code. See "two-out-of-five code".

3.17 Bistable multivibrator. see "flip-flop".

3.18 Bit. An abbreviation for Binary digit and has the value of either True (1) or False (0), On or Off; the basic unit of the binary system.

3.19 Bit and complement. The insertion of parity bits such that for each binary 1 there is a binary 0.

3.20 Bit binary unit. the binary digit has the value of either "1" or “o”, “True” or “False”, “On” or “Off”.

3.21 Bit width. The angular measure of the sector or time measure which defines either the True (1) or False (0) value of a bit.

3.22 Capacity. The total number of counts available from an encoder.

3.23 Code. A number of binary digits uniquely arranged to define each position in a given number system.

3.24 Command. An instruction coded in binary form.

3.25 Complement. The process, act, or result of inverting a logic function or number to the opposite binary state.

3.26 Count error. An omission or mistake in coded output.

3.27 Count transition point. the midpoint of boundary between two adjacent output counts.

3.28 Counts per turn. The total number of code positions per 360° of encoder shaft rotation.

3.29 Data. Any representations such as characters or analog quantities to which meaning is assigned.

3.30 Datex code. A four-bit unit distance binary coded cyclic decimal code which defines the Arabic numbers. Some of its features include:

a. Nine’s complements are formed by inverting one bit per Arabic character.

b. The maximum number of bits which are ON (1’s) in any of the code positions is three.

c. The all “0’s” code and the all “1’s” code are not used, thereby providing an error checking feature.

3.31 Digit. A character used to represent integers smaller than the radix; for example, 0 through 9 in decimal notation.

3.32 8-4-2-1 binary coded decimal. A four-bit binary decimal code. Specifically, the first 10 code positions in the natural binary code which then define the Arabic numbers 0 through 9.

3.33 Excess-3 code. A binary coded decimal representation in which each decimal digit is represented by the binary equivalent plus 3.

3.34 Exclusive OR gate. A logic element with two inputs and one output having the property that if either input is true, but not both true, the output is True; and if both inputs are true or both inputs false, the output is False.

3.35 Flip-flop. A circuit containing logic elements capable of assuming either one of two stable states at any given time.

3.36 Follow mode. A mode of operation for a storage circuit in which the output continuously follows or reflects all changes of the input data.

3.37 Full Indicator Movement (FIM). The total movement of an indicator when appropriately applied to a surface to measure its variations.

3.38 Gate. A logic element having one output channel and one or more input channels, such as the AND gate or OR gate.

3.39 Gray code. A unit distance code obtained by a reflection of each bit in the natural binary code. Also called the reflected binary code. (Named after its inventor, Mr. F. Gray.)

3.40 Hysteresis. The apparent angular width of a transition point as determined by approaching the point from either direction of shaft rotation.

3.41 Inclusive OR gate. A logic element or circuit which operates such that if any input is true, the output is True, and the output is False only when all inputs are false.

3.42 Incremental code. A two-bit binary code used to increment or decrement an external accumulator.

3.43 Index. A single, separate output of an incremental encoder providing one count per revolution.

3.44 Instrument error. See "transition error."

3.45 Interface. Interconnections of one system element to another.

3.46 Latch mode. A mode of operation for a storage circuit in which all encoder contact closures, even momentary 1's, are latched "ON".

3.47 Monostrophic code. A binary code in which only one bit changes between any two adjacent code positions.

3.48 Natural binary code. A binary number system in which the bits are weighted as powers of two, such as 1, 2, 4, 8, 16, 32, and so on.

3.49 Nine's complement. A complement number which is derived by subtracting from nine each of the Arabic numbers of O through 9.

3.50 Noise. Any momentary variation in the steady state resistance of an encoder contact. Usually measured as a momentary fluctuation of the voltage across a load supplied through an encoder contact.

3.51 Not. A shorthand logic notation, usually employing a bar over the symbol or expression, denoting that the complement value is to be taken.

3.52 Number. A mathematical entity that indicates quantity or amounts of units.

3.53 Octal. Pertaining to a number system with a radix of eight.

3.54 Odd-even check. A check that tests whether the number of 1's (or O's) in an array of binary digits is odd or even (synonymous with parity check) .

3.55 Operating speed, maximum. The maximum angular velocity at which an encoder may operate and still maintain specified accuracy.

3.56 OR sate. A logic component having the property that if any one input is true, the output is True, and the output is false only when all inputs are False.

3.57 Parallel data. Data of two or more bits, each occurring simultaneously on separate channels.

3.58 Parity bit. A binary digit appended to an array of bits to make the sum of all bits always odd or always even (synonymous with odd-even check).

3.59 Polystrophic code. A binary code in which, for at least one count transition, two or more bits are required to change simultaneously in going from one adjacent code position to another.

3.60 Quadrature encoder. An encoder that uses two output channels in quadrature (displaced 90°) for position sensing.

3.61 Quantization error. The inherent fixed error associated with digitizing an analog shaft position in that a continuous form of data is being replaced by noncontinuous increments.

3.62 Quantize. To subdivide a range of values of a variable to a finite number of non-overlapping intervals, each of which is assigned a specific value or code position.

3.63 Quantum. The theoretical angular increment of input shaft rotation between count transitions, or subtended by one code position.

3.64 Radial load, maximum. The maximum radial force that may be applied to the encoder shaft in any direction without affecting encoder performance.

3.65 Radix. The number of digit symbols in a number system; the numerical base of the number system.

3.66 Register. A device capable of storing a specific amount of data.

3.67 Reliability. The probability that an observed or sample value of encoder output is exactly equal to the required output.

3.68 Repeatability. The standard deviation of repeated input shaft angle settings to the same count transition.

3.69 Reset. To restore a storage device to a prescribed state.

3.70 Resolution. The measure of code position density expressed as the number of counts for each revolution of the input shaft or the angular portion of a circle subtended by one count. A measure of the smallest angular quantum which can be detected by the encoder.

3.71 Select mode. A mode of operation for an encoder selector circuit in which one set of brushes is selected to be read and another inhibited from being read; also a mode of operation for a system controlling several encoder outputs in which one encoder is selected to be read and all others inhibited from being read.

3.72 Self-checking code. A code in which each expression conforms to specific rules of construction, so that if certain errors occur in the expression the result will not conform to the rules of construction and, thus, the presence of the error is detected.

3.73 Self-selecting V-scan. The V-scan method of reading a polystrophic code (primarily the binary code) in which diode logic circuits are used internally in the encoder to perform the necessary bit-to-bit selection to prevent ambiguity in the encoder output data.

3.74 Serial data. Data consisting of bits occurring sequentially on a single channel.

3.75 Set. To place a storage device into a prescribed state.

3.76 Set-Reset flip-flop. A bistable multivibrator which can be placed in a given state by energizing the set line, or placed in the opposite state by energizing the reset line.

3.77 Shaft angle. The angular position of the encoder shaft measured from the zero reference point in a positive direction.

3.78 Shift register. A register in which the stored data can be moved to the right or left.

3.79 Slew speed. The maximum angular velocity to which an encoder may be accelerated and still regain full accuracy when slowed below the maximum rotation speed.

3.80 Storage. Pertaining to a device into which data can be entered, in which it can be held and from which it can be retrieved at a later time.

3.81 Store mode. A mode of operation for a storage circuit in which data is retained and any changes to the inputs are not reflected in the output circuits.

3.82 Toggle. A bistable multivibrator which can be made to change states by energizing its toggle input.

3.83 Toroid. A three dimensional geometric shape, probably most accurately described as donut-shaped.

3.84 Total count. The number of code positions in the total encoder output.

3.85 Transition accuracy. The maximum difference in angle between the actual and the true positions of a transition between one code position and an adjacent code position.

3.86 Transition error. The difference between the shaft angle at which a code position change should occur and the angle at which it actually does occur, and is usually a measure of the sum of manufacturing tolerances and wear.

3.87 Translate. To convert from one number system to another.

3.88 Truth table. A table that describes a logic function by listing all possible combinations of input values and indicating, for each combination, the true output values.

3.89 Two-out-of-five code. A binary coded decimal code in which each decimal digit is represented by five binary bits of which two are “l’s” and the other three are “0’s”.

3.90 Unit distance code. Same as monostrophic code.

3.91 U-scan. A parallel reading method for preventing ambiguity in the readout of polystrophic codes at the code position transitions by reading one of two sets of sensors depending on the state of a control or selector bit. The term "U"-scan comes from the geometric pattern of the brushes, which has the appearance of a “U” when this technique is used in reading a polystrophic code pattern with a single track and two sensors per bit.

3.92 V-scan. A serial reading method for preventing ambiguity in the readout of polystrophic codes at the code position transitions by reading either of two sensors associated with a given bit, depending on the state of the next least significant bit. The term "V"-scan comes from the geometric pattern of the brushes, which has the appearance of a “V” when this technique is used in reading the natural binary code with a single track and two sensors per bit.

3.93 Zero reference. The input shaft angle corresponding to the midpoint of the transition between full count and zero count.

4.0 GENERAL REQUIREMENTS

4.1 Need for computer control. Computerized control and automation in myriad forms are primary concepts in the development and design of present-day systems. These phenomena are felt with equal impact in the military, industrial, and consumer segments of modern engineering. Greater system complexity and performance capability is creating an increasing demand for devices which will provide rapid, accurate shaft position data. In a majority of cases, digital shaft encoders are used to fill this need.

4.2 Survey of encoders - general. The material presented in this handbook is non-specific in nature and presents a broad survey of the digital encoder field. This handbook does not catalog or describe specific encoder hardware except in the most general terms for the purpose of showing specific examples of applications or usages. For specific information regarding encoder hardware, the reader is referred to MIL-E-85082. This handbook defines digital encoders, explains their theory, design and procurement decisions.

5.0 DETAILED REQUIREMENTS

5.1 Encoder description. Shaft position analog-to-digital encoders are electromechanical devices which convert input analog data in the form of contact closures or voltage levels. Thus, encoders are mechanical to electrical transducers. Sensing of the input shaft position or rate is accomplished by a mechanical drive which positions a coded disc or drum (discs in a multi-turn unit) containing tracks of information to unique positions. The information on the tracks is read out in digital form for display or utilization by other equipments.

5.2 Encoder classification. Encoders are first classified by the method used to read the coded disc, such as contact or non-contact.

5.2.1 Contact encoder. The contact encoder utilizes a direct physical sensor connection in the form of a brush(es) or pin(s) riding on each track of information. Each track then operates as the more familiar generator commutator with conducting and nonconducting segments. For each position of the input shaft, there is a unique combination of conducting and nonconducting tracks which produce a unique combination of conducting and nonconducting sensors. The combinations for various shaft positions (code assignment) are assigned during encoder design. Sensor conduction is read out in the form of “Yes-No” information (conducting or nonconducting circuits), and an output corresponding to the input shaft information is generated. The input shaft data, then, is represented by an output group of “Yes-No’s”, the maximum number of which is determined by the number of sensors used on the disc. Not all sensors are necessarily used to detect shaft data. Additional sensors may be added to an encoder for error checking, error stopping, or other features. The “yes-No” or “True-False” type of output has several advantages. First, it is extremely compatible with electronic circuits as they are easily designed for this “On-Off” type of operation. Second, it can be represented easily by the binary number system, a system having a base or radix of two. In the binary system, only two digits are used, normally one and zero. In most types of encoders, one is normally used to represent “Yes” (“True” or “On”), and zero represents “No” (“False” or “Off”). Third, the electronic circuits can be designed to operate using Boolean logic, as in a digital computer. Thus , a group of rules already exists and encoders can utilize digital circuitry for readout. The digital data output of an encoder may be in any form or code to which auxiliary equipment can respond. However, one code normally serves the design parameters or auxiliary equipment better in that less electronics might be required, better noise rejection could be obtained, the zero reference may require shifting for reset, or error detection circuits are desired. Common output codes using the binary number system are presented herein to illustrate the various types of codes available.

5.2.2 Non-contact encoder. The non-contact encoder is similar to the contact encoder except that direct physical contact with the coded disc is not utilized and sensing of disc and track position is accomplished by magnetic, optical, capacitive, inductive or other means. Magnetic sensing may utilize a ferrite coded disc with raised code patterns. Optical sensing may be performed by photocells which detect a lamp output shining through the clear segments of a coded disc with clear and opaque segments. One method of capacitance sensing utilizes the cyclic change in capacitance between two stators and a rotor driven by a constant speed motor. Due to the variety of non-contact encoders, they are described individually in detail in succeeding sections of this handbook.

5.3 Functional systems of encoder. The most efficient method for generating a digital signal (digitizing the variable properties of a rotating shaft) is to couple the shaft mechanically to a shaft encoder. Operating in conjunction with suitable output circuits, a shaft encoder can produce a digital word representing the position, direction, speed, and amount of rotation of the shaft. As shown on Figure 1, there are four basic functions in the design and development of a digital shaft encoder system:

a. Input processing function.

b. Detection function.

c. Logic processing function.

d. Output function.

5.3.1 Input function. A simple block diagram for an encoder is shown on Figure 2. The input device is a coupling between the rotating shaft and the cam switch. The cam switch, which alternately opens and closes once for each 360° of rotation of the input shaft, is the detector. The logic processing for this device provides a one-bit digital word representing the position of the shaft. The battery and lamp provide the output. A logical "1" is indicated when the lamp is on and a logical “O” when the lamp is off. For any position of the input shaft from 0° to 180°, the lamp will be off. For any shaft position between 180° and 360°, the lamp will be on. This is an elementary encoder system of limited resolution and accuracy, but all of the important elements are represented. The only shaft positions this rudimentary encoder can indicate are the 180° and 360° positions since at these points the light condition changes (on to off; off to on). However, some rough measure of shaft speed is indicated, at least in relative terms, since the speed at which the light condition changes is a direct function of shaft speed. If shaft speed is sufficiently slow to permit careful, laborious observation, the sequence of light conditions can further indicate the direction rotation. However, it is obvious that the applications for a device of this sort are limited. In subsequent sections of this chapter, variations of this system will be developed to illustrate the fundamental design techniques for improving such performance factors as resolution, speed and accuracy.

5.3.1.1 Input devices. To digitize a shaft rotational variable, a means must be provided to couple the mechanical energy (rotation) of the shaft to the encoder and condition this mechanical input to a form best suited to the particular needs of a given system. Sometimes the rotating shaft can provide the required input with no more complication than a simple mechanical coupling. At other times, additional gearing is required to step up or step down the speed of the shaft input. In other cases, some conditioning may be required to compensate for such matters as torque, inertia, resolution, or accuracy. In any case, some method is essential for transforming the rotational energy of the shaft to be measured to the encoder in a form suitable for the digitizing function.

5.3.1.2 Input design characteristics.

5.3.1.2.1 Number of revolutions. The main factor in the design of input devices is the number of revolutions of the encoder shaft required for a full scale output. Taking a required full scale output of 1,000 counts (0 to 999) as an example, the encoding of a shaft position can be accomplished by:

a. An encoder that counts 1,000 equal increments for each 360° of rotation of the input shaft.

b. An encoder that counts 100 positions of each 360° of rotation of its input shaft and, therefore, requires 10 revolutions of its input shaft to produce a full scale output.

c. An encoder that counts only 10 positions per 360° of input shaft revolutions and, therefore, requires 100 revolutions of the input shaft to produce a full scale input.

The encoder described in a. can meet the basic design requirement using a directly coupled input method. For the encoder described in b., the input device requires a 10 to 1 step-up gear arrangement; and these gears must incorporate a degree of accuracy somewhat greater than the overall encoding accuracy required. An input device incorporating a 100 to 1 step-up gear train is necessary for the encoder described in c.; and here again, gearing accuracy must be better than the order of encoding accuracy.

5.3.1.2.2 Torque and inertia factors. In the design of encoder input devices, torque and inertia are also important considerations. For example, in the encoder described in a., the inertia presented to the driving shaft is the inertia of the encoder itself. In the encoder described in b., the reflected inertia to the driving shaft is increased by a factor of 100 (the square of the gear ratio), while the reflected inertia for the encoder described in c. is 10,000 times that of the encoder. These increases in inertia must be considered in addition to the added inertia due to gears themselves. Driving torque requirements are also affected by the addition of step-up gearing in the input device. The torque required to operate the encoder described in b. is 10 times the torque applied to the input shaft. In the encoder described in c., the operating torque is 100 times that applied at the input.

5.3.1.2.3 Overall accuracy. Complexities in the input devices will also affect overall encoder accuracy. In encoders with directly coupled inputs, the accuracy is relatively unaffected at the input. In geared-up units, the overall accuracy becomes more nearly a function of gear accuracy as gear ratio increases.

5.3.1.3 Input problems. The detection, logic processing, and output methods used in the one-bit encoder shown on Figure 2 are extremely simple and reliable, but limited. Consider the problem where the input shaft is rotating at a speed of 1,800 rpm. At this speed, the cam switch would be actuated twice per revolution of 108,000 times per hour of continuous operation. In a 24-hour period, the cam switch would be subjected to nearly 2,600,000 operations. Switch wear and replacement would rapidly become a major problem. Moreover, the resulting output would be of questionable value. With the light flashing at a rate of 300 Hz, it would appear to be glowing steadily to a human observer. Much additional instrumentation would be required to use an output supplied in this form.

5.3.1.3.1 Length of service life. By including a 100 to 1 step-down gear train as part of the input device, the cam switch would operate once for each 100 revolutions of the input shaft. This technique would substantially increase the service life of the cam switch. Also, the output would be supplied at a rate of 0.3 Hz, a rate more suited to human observation. However, the system would no longer be implemented to present even rough shaft position. With the cam switch rotating once for each 100 revolutions of the input shaft, the light would be on for the first 50 revolutions and off for the last 50 revolutions of each 100-revolution operation cycle. By modifying the input device, the service life of the system is improved and the functional application of the system changed from a device for indicating shaft position to a device for counting shaft revolutions or shaft total angle. Under these circumstances, the device would not derive any meaningful data on rotational direction or speed.

5.3.1.3.2 Slow rotational speed. Next consider the case where rotational speed of the input shaft is extremely slow; for example, one revolution per hour. Under this circumstance, a directly coupled input would certainly impose no undue system wear; and the shaft position data would be extremely easy to derive within the obvious resolution and accuracy limits. However, the addition of a 100 to 1 step-up gear train as part of the input device would effectively divide each revolution of the input shaft into 100 equal increments. This technique would provide an output indication for each 3.6° of shaft rotation, and would increase the resolution by a factor of 100. The output indication would be presented at a rate of approximately 1.6 cycles per minute, well within human observational capability. The output data would not allow the finding of a definite angular position (180° and 360°) as in the directly coupled configuration. More accurate incremental position would be available, however, in a form from which exact angular position could be derived.

5.3.2 Detection function. In the basic encoder system shown on Figure 2, detection is provided by the one-lobe cam switch, a relatively crude device. The cam switch used in the example shows the basic difference between encoders and their analog ancestors. Use of digital readout is an improvement in kind rather than degree. The digital approach provides potential accuracy and reliability unattainable in even the most advanced and sophisticated analog devices. The detection function is the heart of an encoder system. The basic example illustrates the detection principle, high-precision switching or toggling. The detection method usually defines the encoder type. Even the simplest encoders in present-day use employ detection schemes which are far more precise than the cam switch used in this elementary functional explanation.

5.3.2.1 Detection devices.

5.3.2.1.1 Two switching circuits. Some measure of the potential accuracy achievable with the digital method can be shown by adding a second cam switch and lamp circuit driven in common with the first as shown on Figures 3 and 4. By arranging the second switching circuit to produce a light indication out of phase with the first, the capability of the encoder is doubled. The addition of more switching elements produces a similar progressive improvement. With two switching elements, the input shaft position can be detected for four segments of the 360° of input shaft rotation. Now, with two switches, there is a choice of coding techniques available. If the second cam is arranged to energize the second lamp at 90°, reenergize it at 180°, energize it again at 270°, and deenergize it at 360° (see Figure 3), this detection scheme will produce a natural binary, two-bit code representing the four discrete quadrants of input shaft rotation. However, the second cam could also be arranged to energize the second lamp between 90° and 270° and deenergize the second lamp between 270° and 90° (see Figure 4). This detection method would still produce sufficient data to divide the rotation of the input shaft into four equal segments and the encoder would produce a two-bit, Gray or Reflected Binary code output. Using this last technique, the alignment of the cams is much less critical since only one switch changes at a time to increment the output count.

5.3.2.1.2 Separate switch assemblies. The use of a series of separate switch assemblies as a detection technique is impractical for actual systems. This approach, used here purely for illustrative purposes, is bulky, heavy, inaccurate, and lacks the speed of response essential in modern systems. However, the cam switch detection scheme provides a concrete example of the basic detection principle in digital encoders: high-speed, precision switching. Essentially, the functions involved in the detection process--interrogation, scanning and coding--contribute to the basic goal of converting a rotational mechanical input to a series of electrical pulses in a digital form which is a precise representation of selected input characteristics.

5.3.2.1.3 A mechanized disc. Detection in an encoder system is a matter of alternately opening and closing an electrical circuit to produce a group of output pulses. In almost all cases, present-day encoders accomplish this function through the use of a special disc, attached to the input device, and mechanized to rotate in response to the movement of the mechanical shaft input. The surface of the disc is divided into alternating segments of conducting and non-conducting area. The surface pattern of the disc represents the coding technique and the interface between the disc and the encoder output. The pattern used for picking up the code is called a scan. The code and scan define the encoder type and category and, in a large part, establish the performance and operating parameters for the encoder. The pattern for an encoder disc with a natural binary code is shown on Figure 5.

5.3.2.1.4 Basic detection techniques. Detection can be accomplished through one of two basic techniques: contacting and non-contacting. Using the contacting method, a set of stationary conductors (such as brushes or pin contacts) actually touches the rotating disc and readout is effected by conductive means. When the brushes are in contact with the conductive segments on the surface of the disc, the detection circuit conducts. When the brushes contact the non-conductive segments, the circuit is open, hence the high-speed, precision switch action in response to rotation of the input shaft. Non-conducting detection methods include magnetic, optical, and capacitive techniques where the switch action is accomplished by electromagnetic, photo-electric, or electrostatic means, respectively.

5.3.2.2 Detection design characteristics. The four basic types of detection (brush or contact, magnetic, capacitive, and optical) can be further divided into two categories: incremental and absolute. Incremental detection provides a series of identical output pulses for successive increments of changing input shaft position. These pulses must be subsequently counted to provide meaningful intelligence on actual shaft position. Absolute detection provides a uniquely coded signal corresponding to the exact position of the input shaft. Using the absolute detection method, shaft position can be determined directly. Since the incremental method provides an identical output for each quantized shaft position, the two basic methods can be added and combined with appropriate logic processing to represent the total motion of the input shaft, either by counting from a zero reference or by storing the last total and adding or subtracting only the last change. This combination technique (full word or direct reading) provides a unique output for each discrete shaft position within the resolution limits. Using this method, positional data can be stored and retained despite such problems as power failure or noise transients. Although this method requires no further coding or counting, logic processing is required to convert the output to another form for some particular uses.

5.3.2.3 Detection problems.

5.3.2.3.1 Incremental detection. In incremental detection, the rotating disc has at least one track of equally spaced segments and an appropriate sensing arrangement. The resulting rate of output pulses is a function of input shaft speed. By using a second sensing member displaced one-half quantum from the first sensor, direction of rotation can be detected. The resulting lead-lag data is resolved and applied to an up-down counter as part of the logic processing function. The data is derived in increments and must be accumulated and stored in logic processing circuits external to the detection function if it is to represent shaft position.

5.3.2.3.2 Absolute detection. The mechanization and operating scheme in absolute detection devices is essentially the same as discussed above for the incremental method. The important difference lies in the arrangement of the segments on the rotating disc where the incremental method employs fairly standardized patterns. In the absolute detection method, unique patterns designed especially for a particular task are used. There is also a major difference in the nature of the resulting output. Where the incremental detector produces a group of identical pulses representing the amount of input shaft rotation, the absolute device produces a uniquely coded output signal for each precise position of the input shaft. There are, of course, limits to the number of precise, discrete positions which can be detected and, consequently, a limited number of possible unique outputs representing those positions. The degree of exactness and the number of unique shaft positions that can be detected is the measure of accuracy and resolution for an absolute detecting device. It is often advantageous to combine the incremental and absolute methods to gain some of the benefits of both techniques.

5.3.2.3.3 Ambiguity. Regardless of the precision with which an encoder system is designed and constructed, it is inevitable that certain inherent inaccuracies will arise from the fundamental design problem of converting an analog quantity of infinite variation to discrete, digital terms. The sensors must be placed in fixed positions. At certain times there are narrow intervals of partial transition from one position to the next where some sensors detect the next position while others continue to sense the previous position. Readouts taken at these times will not necessarily interpolate between the two positions. As a result, random output signals can be developed which represent either non-existent or erroneous input shaft conditions. In either case the output will be ambiguous and will impair overall system performance. There are a number of methods used to avoid ambiguity and most encoders employ one of the possible design options.

a. In some applications the problem is avoided by inhibiting readout during transition intervals; better no output than a wrong one.

b. A more general approach is the use of either a coding or scanning technique developed to avoid ambiguity. Binary codes which change only one digit at a time (for example, Gray code) can be used, but this output must be converted to a form suitable for use in digital equipment by appropriate logic processing.

c. A special scanning method, referred to as V-scan, can also be used to avoid ambiguous outputs. Sensors are arranged in a V-shaped pattern with two sensors used for all tracks except the least significant. One of the two sensors is selected to read alternately by logic processing circuits. Generally, in V-scanning, the sensor is not allowed to read closer to the edge of a disc segment than 25 percent of the segment length.

d. A number of methods for avoiding ambiguity are possible, both mechanical and electrical. However, the selection of a proper code will most efficiently solve the ambiguity problem without the need for mechanical concessions or duplicate sensors.

5.3.3 Logic processing function. The signals generated by the detecting function require precise timing and control. This task is accomplished through the logic processing function. The exact characteristics of logic processing are a function of the code and scan techniques. Often the logic processing function is part of the scanning process, which makes it difficult to separate the two functionally. However, certain logic processing functions are common to most families of encoder applications. The general nature of these common logic functions is discussed in this section.

5.3.3.1 Logic devices. Taken as a whole, the logic processing function, operating in conjunction with the detection process, establishes the operating mode for an encoder system. Selection and implementation of specific design options for logic processing will determine encoder system capability. Logic conditioning is a powerful tool for extending the performance of a given complement of mechanical system components. In cases where space or weight is a problem or for highly specialized encoding tasks, logic techniques can be paired with relatively common encoders to meet demanding requirements. Rearrangement and redesign of standard electronic components (diodes, resistors, capacitors, and so on), which are the basic building blocks of logic circuits, is often an easier task (or may yield a more reliable system) than complete redesign of a totally unique encoder system for an unusual application. In other cases, computer or electronic equipment may be at a premium or scanning and coding may take precedence. Particular design parameters and system performance goals must be evaluated and carefully weighed before deciding whether primary emphasis should be placed on the detection or the logic processing function. Thus , a thorough understanding of the logic processing function is essential to efficient encoder design and utilization.

5.3.3.2 Logic design characteristics. Consider the example of the elementary cam switch encoder shown on Figure 2. The basic encoder functions are represented in this crude device. Included are a directly coupled input, a single cam-operated switch to perform detection, and a lamp circuit to provide an output. However, logic processing (the derivation of meaningful intelligence concerning the condition of the input variable) must be performed manually. It can readily be seen that the overall efficiency and utility of this system depend on the skill, the dexterity, and the reasoning ability of the human observer or operator. Assume that the input variable is the mounting chuck of a rotary machine tool hidden from the operator’s view by a safety guard, and the object of the encoder is to display positional information to the machine operator for initial machine setup. When the lamp is on, the chuck is correctly positioned to accept rough stock; when the lamp is out, stock should not be inserted into the machine. The simple device is totally adequate to this task; a more complex or sophisticated device would not be cost-effective. The logic processing function is performed by the operator who merely observes the lamp. However, more complex encoding tasks impose increasing demands upon human skill and manpower. In fact, the requirement for logic processing in modern systems precludes manual readouts and necessitates a more sophisticated approach. For reasons of efficiency and economy, electronic devices provide the best solution to this problem. In incremental encoders which can detect the amount and direction of input shaft rotation, the logic processing problem consists of counting revolutions (or incremental portions of a revolution) , deriving the direction of rotation, and relating this data to some time reference to develop information on shaft speed.

5.3.3.3 Logic processing. To illustrate the basic principles of logic processing, consider again the one-bit cam switch encoder shown on Figure 2. Assume that the input variable is a shaft rotating at some changing and unknown speed and that the encoding task is to derive data on the speed and number of revolutions. An operator equipped with a stop watch, paper and pencil would have to monitor both the light and the watch, count the on-off cycles, and record the count for each series of timed 60-second periods. The resulting paper and pencil record would be a history of total shaft revolutions and shaft speed expressed directly in revolutions per minute. But as shaft rotational speed increased, the operator would have to be very alert and highly dexterous to keep an accurate count. Some increase in accuracy is possible by putting a second man on the job; one to watch the light and one to act as timekeeper. Additional operators could be added to help count lamp cycles for smoother transition between the one-minute time increments and to afford the other operators some rest and relief. However, the speed of shaft rotation detectable by even an infinite number of operators is limited to the flicker frequency which the human eyes can detect.

5.3.3.3.1 Limitations. There are a number of possible input variables which this array of manual data could not deliver, such as changes in the direction of shaft rotation or oscillation of input shaft. These shortcomings are not due to the inadequacies of the logic processing scheme; the detection method simply does not detect these variables.

5.3.3.3.2 Advantages of a two-bit encoder. But what if the two-bit encoder shown on Figures 3 and 4 were being used for the same task. In this situation, the light pattern observed by the human logic processing team would follow the sequence shown in Table I. Considerably more information is now being displayed and a greater variety of data can be observed and recorded with a substantially greater degree of accuracy. Althought the speed and quantity of encoder information that can be recorded is still limited by human performance parameters, the operators can now record total rotation speed and position to an accuracy of a quarter turn, as opposed to the half-turn accuracy possible with the one-bit encoder. the direction of shaft rotation, which was not easily detectable with the one-bit encoder, can now be derived by observing the sequence of lamp indications. The lamp sequence shown in Table I indicates clockwise rotation of the input shaft and the reverse pattern would result from counterclockwise rotation. Oscillation of the input shaft would produce no indication for some conditions and erroneous or ambiguous outputs for others. in either case the condition could not be detected. If, for example, the input shaft were oscillating between the limits of 45° and 60°, the output would be a continuously extinguished lamp. The operator would not be able to distinguish this condition from a stopped shaft or from extremely slow rotation. If oscillation were occurring between the limits of 140° and 200°, the output would be the same as for normal rotation, but at a rate three times faster than the actual speed of shaft movement, since a swing of only 120° (60° CW and 60° CCW) would produce the same output as a full 360° rotation.

5.3.3.4 Logic circuit problems. The two-bit encoder, with its two-fold increase in resolution, would indicate oscillation of the input shaft as a function of the lamp sequence. However, ambiguity would still be a problem in the two-bit encoder, but of a different sort. As shown in Table I, the indicator lamps and the cam-switch detectors which control them must change condition simultaneously at 180° and at 360°. Any physical misalignment or lack of synchronization between the operation of the switches will cause one switch to actuate before the other. This will result in a momentary erroneous output. The physical nature of switches is such that exactly synchronous operation is not possible and, therefore, ambiguous outputs are inherent in the two-bit encoder configuration shown on Figures 3 and 4. A logic processing circuit is required to overcome this weakness.

5.3.3.4.1 Switching condition utilizing two cam switches. Figure 6 shows the ideal theoretical switching condition for a two-bit encoder utilizing two cam switches, A and B. As stated above, both switch A and B would have to change condition simultaneously at 360° and 180°. Since this cannot be achieved in a practical working system, the switch A function can be performed by two switches, A-lead and A-lag. This technique is called lead-lag switching. The lead-lag switching pattern is shown on Figure 5. Switch A-lead is mechanized to operate at some point slightly preceding the critical points (360° and 180°), while the operation of switch A-lag is offset to some point slightly after the critical points. By replacing switch A with two switches mechanized for lead-lag operation, no two switches are required to operate at exactly the same instant and the ambiguity is eliminated. The lead-lag switching technique is shown schematically on Figure 7. Switch B, mechanized to operate at 0°, 90°, 180° and 360°, serves the dual function of controlling Lamp B and selecting whether switch A-lead or switch A-lag controls the operation of Lamp A. Switch A-lead operates only when switch A-lead is selected and, conversely, switch A-lag operates only when switch A-lag is selected. Consequently, all changes in output indication are centrally controlled by the action of switch B. No more than one switch operates at any one time, and the visual output indication changes only in response to the action of switch B, the central controller. The underlying principle of the foregoing example is known as automatic sensor selection. This basic circuit approach for overcoming ambiguity is used extensively in the design of digital shaft encoders.

5.3.3.4.2 Increasing complexity of logic processing circuits. As the performance requirements for encoder systems increase, the complexity and sophistication of logic processing circuits increase proportionately. The speed, accuracy, and resolution requirements and the increasingly large volume of output data needed for modern aerospace and industrial applications eliminate the possibility of using human logic processing in most encoder systems. Stop watches, operators with paper and pencil, and even carefully designed cam-switch circuits are too slow for all but the most basic and rudimentary tasks. High-speed counters, timers, storage and signal conditioning circuits making wide use of solid state microelectronics and digital logic circuits are the building blocks used for logic processing in the overwhelming majority of present encoder systems. However, the basic logic processing tasks are the same:

a. Timing.

b. Counting.

c. Detecting.

d. Controlling.

e. Conditioning.

5.3.4 <u>Output function.</u> Conversion of a shaft angle position into a digital signal is the purpose of all shaft encoders. This digital signal is the output of an encoder system and can be developed to represent a host of input variables including the speed, direction, and amount of shaft rotation and the absolute position of the input shaft. Encoder outputs must be developed in a form suited to the associated sensing or recording device. Since encoders are most commonly employed as a component part of a larger system, the encoder configuration and design must integrate with and be subordinate to system requirements. This fact is true of each functional section of an encoder, but output signal processing is especially important since the output signal must interface directly with peripheral components and the overall system. Conditioning of the final signal output offers great potential flexibility in encoder development by enabling the designer to use the input, detection, and logic processing techniques best suited for such considerations as weight, space, speed, resolution, and accuracy (that is, encoder performance). These techniques may then be integrated with output techniques to put the signal in the form required for system interface.

5.3.4.1 <u>Output devices.</u> Encoder outputs are usually produced in the form of serial or parallel pulses representing input shaft movement in some digital code. Even where there is no movement at the input, shaft position can be derived in digital form using static voltage or current levels. It is rare to design an encoder without some system application in mind, and it is the system requirement that determines the amount and the type of output processing. Generally, the major types of output processing can be categorized as amplification, storage, and shaping.

5.3.4.1.1 <u>Amplification.</u> The basic encoder systems shown on Figures 2, 3 and 4 provide outputs to simple indicator lamps in the form of a DC voltage supplied by batteries. The output signal can be considered the energizing voltage if the indicator lamps are not part of the encoder, or the output can be considered the visual light signal if the lamps are integral to the encoder. In either case, the output requires no special conditioning since a DC voltage is adequate to drive the indicator lamps and the lamp signals can convey the necessary intelligence to a human observer. But suppose the indicator lamps are at a remote location, as might be the case in a missile fire control system. The encoder might be used to detect the position of a control valve located at a firing site; and the indicator lamps and the operator would probably be in a remote bunker or control room, perhaps as far as a mile away. The losses inherent in transmission lines of this length would render the DC output totally inadequate. One solution would be to use an AC voltage source and an AC indicator lamp. Another possibility would be the use of some form of amplification to compensate for line loss. In any event, this situation demonstrates the basic output design task of amplification including such associated problems as impedance matching and level setting. In most modern, high performance systems, this function is performed using solid state electronic amplifiers to provide an output of the level required to drive ancillary devices.

5.3.4.1.2 Storage. In the cam switch encoder used as an example throughout this section, the storage function is performed by an operator using a stop watch to provide a time reference and paper and pencil to store pulse information. Again, this function is usually accomplished electronically in most systems. In incremental encoders the array of identical output signals representing some discrete amount of input shaft movement must be sensed (usually at a very high rate) and a count accumulated which is related to some precise time base. This stored count is the elemental data from which shaft speed, direction, position, and relative movement can be computed, and then presented in a form readily comprehended by people (for example, decimal count) or applied to other circuits for further processing and refinement.

5.3.4.1.3 Shaping. Since the output of most encoders is applied to other electronic processing or computing equipment, it is usually necessary to shape the pulse output and condition it for further use. The pulse shaping or pulse forming function of encoder output circuits typically includes such operations as filtering, clipping, inverting, differentiating, and integrating. These processes, applied singly or in combination, serve to modify the encoder output and produce pulses of the shape, amplitude, polarity, duration, and spacing required by ancillary data and information systems. For example, a steady DC voltage sequentially applied and interrupted by the action of switch contacts produces a square wave whose polarity and amplitude are determined by the nature of the power supply. The duration and spacing of the pulses will be a function of the timing of the switch action. Digital techniques and digital equipment depend on a fair amount of regularity in the pulse signals for proper operation. If the variables in a pulse signal are shape, duration, amplitude, frequency, and total number, it is most efficient to standardize as many of these variables as possible and allow only one of them to change as a function of the intelligence contained in the signal. Thus, the shaping circuits included in encoder systems serve to standardize those pulse characteristics that do not convey actual shaft angle data and condition those standard elements to the form required by the function which is to be performed.

5.3.4.2 Output design characteristics. The human sight faculty is highly generalized which makes it possible for people to detect and respond to a broad spectrum of light stimuli. But this generalization limits the capability of a human to detect and count the cyclic flickering of a lamp, even at relatively slow frequencies. It is paradoxical that the tedious chore of watching a light flash off and on is, at the same time, beneath human potential and beyond it. People do not make very good sensors and people are capable of much more important and creative work. Therefore, the output from a digital encoder system is rarely produced for direct human observation. The output function amplifies, stores, and times the encoder output and converts it to a format usable by electronic display, recording, processing, or computing equipment.

5.3.5 Summary of interrelation of functions. The four basic elements of an encoder system (input, detection, logic processing and output) are closely interrelated and each affects system performance, operating mode, reliability and overall capability.

5.3.5.1 Input. The input function can be used to condition the mechanical factors affecting the operation of the rest of the encoder. However, speeding up or slowing down encoder operation relative to input shaft motion also imposes penalties in torque, loading, and inertia. These factors must be carefully considered in encoder design and selection.

5.3.5.2 Detection. The detection function is usually performed in modern encoders by a coded disc attached to the input. The rotating disc acts as the control element of a high precision switch selectively opening and closing an electrical circuit in response to variations in the input and in accordance with the code pattern etched on the disc. The pattern determines the type of shaft angle data that the encoder will provide: incremental or absolute. The other half of the detection function is the readout technique, which is the method for sensing the code pattern. This is accomplished conductively in contact encoders, electrostatically in capacitive encoders, electromagnetically in magnetic encoders, and photoelectrically in optical encoders. The physical arrangement of the sensors in the detection function is called the scan of the encoder. The combination of code and scan determines the basic encoder characteristics and operating mode.

5.3.5.3. Logic processing. Logic processing can be an integral part of an encoder or can be accomplished by circuits external to the unit. These circuits are primarily devoted to solving ambiguity problems inherent in some otherwise attractive scanning methods. In addition, incremental encoders use logic circuits for such functions as counting, timing and detecting the directions of the input shaft rotation. In absolute encoders, logic circuits are also used for sensor selection and control and for signal conditioning.

5.3.5.4 Output. The digital output of an encoder often requires additional final processing to adapt it to interfacing system equipment. This processing consists mainly of amplification, storage, and shaping. Amplifier circuits serve to set output levels and match impedance. Storage circuits are sometimes employed to accumulate individual output signals and form them into groups of the proper size, sequence, and order. Shaping circuits perform such functions as pulse forming, integration, and differentiation to condition the output for efficient interface.

5.3.6 Conclusion - functional systems. Shaft encoding, while not new, has come into prominence because of increasing requirements for digital systems. Because of this need, more engineers and designers are finding wider applications for encoder systems. For these devices to be used effectively, a thorough understanding of encoder principles and functions is essential. The various functional elements of an encoder and their interaction will affect system performance. To select the proper device for a given application, each of the elements must be carefully analyzed, its effect or contribution to system effectiveness evaluated, and each contingency traded off to derive the best unit for the job. Since coding and scanning are the heart of an encoder system, these elements should be considered first to assure the required level of accuracy, resolution, speed, and reliability. The other elements should then be selected on a basis of real and meaningful contribution to operational efficiency.

5.4 Encoder types.

5.4.1 Encoder techniques. The major differences among the various types of encoders are the methods used to mechanize the detection function; the technique for developing an electrical output in response to a mechanical input. The details of this high-precision switching process represent the single most important design feature of an encoder system, so important that encoders are identified and typed in accordance with this characteristic.

5.4.1.1 Detection. There are two broad divisions in encoder devices - contacting and non-contacting. Detection is most commonly effected by attaching a disc to the input shaft. The disc rotates as a function of the mechanical shaft input. The face of the disc is patterned in accordance with a code representing the variables to be detected and the required output (see Figure 5). The coded segments on the face of the disc function as the equivalent of open or closed switch contacts. In contacting encoders the readout elements of the detection process actually ride on the face of the rotating disc, in physical contact with it, and the varying output is developed conductively. Conducting (or closed-contact) segments of the disc alternate with insulating (or open-contact) areas. In non-contacting encoders the output is developed without physical contact between the disc and the sensor by electromagnetic, electrostatic, or photoelectric means.

5.4.1.2 Output. As in contacting devices, the segmented areas of the disc are divided into functional closed-contact and open-contact areas in accordance with a selected code; the derived output is a function of the movement of the input shaft and the details of the detection process. Whether the disc segments modify current flow, electrical charge, flux lines, or interrupt a light beam, their basic purpose is the same--to produce a controlled electrical signal which varies as a function of a mechanical input variable in accordance with a selected digital output code. For unusual applications, these techniques can be combined to produce special encoder types. The basic encoder types are discussed from both a theoretical and a practical point of view in the following text. A discussion of some special types of encoders is included wherein the various basic and special types are compared and evaluated to provide some rules for design and procurement tradeoffs.

5.4.2 Shaft encoder types. Currently, there are four basic types of digital shaft encoders whose primary difference lies in the technique used for reading out the data:

a. Contact encoders which produce a conductive output through pins or brushes making contact with a revolving, segmented disc.

b. Magnetic encoders which produce an output magnetically as in drum memories or tape recorders.

c. Optical encoders which utilize photoelectric techniques to effect readout.

d. Capacitive encoders which produce outputs electrostatically.

Functionally, a digital shaft encoder can be considered a high-precision switch falling into two categories, incremental and absolute. Incremental encoders supply a given series of identical pulses for each 360° of shaft rotation. Shaft position is derived by counting the output pulse. Since each pulse represents a known increment of shaft rotation, the number of output pulses is a direct function of the amount of shaft rotation. The absolute encoder produces a uniquely-coded output signal for each discrete position of the input shaft. Most types of encoders enjoy wide acceptance and use. The specific device employed in a given situation depends upon such considerations as accuracy and resolution requirements, space and weight limitations for peripheral circuits, the complexity of the encoding task, the speed and frequency at which outputs must be supplied, and many related system and hardware design parameters. Contact encoders, because of their low cost and simple construction, are in widest use today. Magnetic encoders have the advantage of accurate, reliable long-life operation in high-speed applications which make the simpler, lower cost contact encoder impractical. Optical encoders provide great resolution capability, but are expensive and complex units in terms of initial acquisition and life-cycle ownership costs. The higher cost of optical encoders as compared to that of contact and magnetic types has limited their use to those applications where resolution requirements are stringent. However, the cost of optical encoders is decreasing as demand and the volume of production increase. Capacitive encoders are not widely used in present-day systems. Although some improvement in accuracy and resolution is theoretically possible through the use of capacitive output coupling, there is an increased reliability risk in using this relatively untried family of devices.

5.4.3 Contact encoders.

5.4.3.1 Background - contact encoders. The earliest contacting encoders employed cantilevered brushes as the sensing element. Brush encoders are still in widespread use today. More recently, the overall performance of this type of encoder has been improved by the development of a pin contact sensing technique.

5.4.3.2 Description. In contacting encoders the disc contains a series of concentric rings or tracks which are thin metallic conductive strips joined at their base as shown on Figure 8. The four tracks shown on Figure 8 represent a binary code consisting of 2°, 2°, 2°, and 2°. The associated contact sensors are identified as B_0, B_1, B_2, and B_3. The numerals 0 through 15 represent the least significant digits. Discs in presently available contacting encoders may contain up to 30 tracks, one of which is a solid, unsegmented concentric ring (not shown on Figure 8) that functions as an electrical return path. As the disc rotates, the sensors alternately contact conductive strips and adjacent insulators, producing a series of square wave patterns. Any patterns that can be produced photographically can be reproduced on an encoder disc and may include uniform or non-uniform tracks, tracks that are out of phase with respect to one another, and other unusual configurations used for special control applications. However, the most common use of encoders is in measuring shaft position where any non-uniformity is a source of error.

5.4.3.3 Design problems.

5.4.3.3.1 Segment placement and eccentricity. Two common difficulties associated with track patterns are: (1) non-uniform spacing of individual segments, and (2) eccentricity in the placement of tracks. Non-uniform spacing produces an output waveform that is not symmetrical and thereby produces positional error. Eccentricity is more subtle in nature, but produces a once-per-revolution error. Figure 9 shows a typical problem in pattern eccentricity. The center of the pattern is displaced from the center of rotation by an amount, e, causing the velocity of the track to change in proportion to its radius. Thus , a typical bit may have a velocity of ω (R-e) as it passes the readout sensor. Intermediate bits will have proportionately varying velocities. During every revolution, there is an effective sinusoidal change in position that is reflected as a velocity error in the output. This problem is minimized through precision manufacture and eliminated by using two contacting sensors located 180° apart. One set of contacts will detect a minimum point while the opposing set detects a maximum. The added outputs from the two sets of sensors will be almost independent of eccentricity errors.

5.4.3.3.2 Segment and sensor size. In addition to the problem of segment placement, the potential performance of contacting encoders is limited by problems of segment size since the accuracy and resolution of the device is a function of this characteristic. The smaller the individual disc segments, the smaller and more exact are the incremental differences in shaft input position that can be detected and digitized. This characteristic, in turn, interacts with the size and placement accuracy of the contacting sensors. It is currently feasible to fabricate encoder discs with segments as fine as 0.001 inch or less. However, to use a disc of this exactness and precision, a correspondingly precise set of contact pins or brushes would be required and placement tolerances for the sensors would be even more demanding. Currently, contacts can be precisely manufactured to dimensions of 0.001 to 0.002 inch. This dimensional accuracy will vary as the contacts are subjected to wear, and bridging of segments would soon occur. However, a more serious limitation results from the problem of sensor positioning which would have to be held to approximately 0.002 inch to produce an output count in a correct binary form. Generally, the finest usable segment width for a contacting encoder is 0.005 to 0.010 inch which results from the practical problems of contact fabrication and placement accuracy. The overall resolution obtainable from devices of this sort is in the order of 2 to 15 seconds of arc.

5.4.3.3.3 Low input shaft speed. Besides the problem of high resolution, contacting encoders are limited to relatively low input shaft rotational speeds. Actual limits will vary with such factors as the physical diameter of the encoder, the amount and type of mechanical input conditioning that is possible, and the amount of use and wear that is expected. In general, contacting encoders with a diameter of 1 to 2 inches are limited to input shaft speeds of approximately 200 rpm.

5.4.3.4 Pin contact encoders. A more recent development in contacting encoders is the pin contact device which uses as the sensing element three spring-loaded pins operating in parallel rather than the conventional cantilevered brush assemblies. Pin contact encoders have demonstrated a marked improvement in life expectancy over the brush types. The mechanical features of the pin contact units provide good environmental resistance, including the ability to operate accurately and effectively under shock conditions up to 150 G’s and in vibration environments of 30 G’s at frequencies ranging from 5 to 2,000 Hz. A typical pin contact encoder, as shown on Figure 10, provides fixed contact location. Since the contact pins are securely mounted in a molded pin cage, all lateral movement of the pins can be held to extremely close tolerances. Using sets of three contacts establishes triple redundancy for increased reliability, and the location of each of the three pins in a set is designed to give different wear paths on the disc. Brush-type sensors induce a single wear path. By filling the pin cavities with the same fluid used to lubricate the face of the disc, hydraulic damping is produced which eliminates contact bounce and the attendant surface noise. Figure 11 is a contact encoder which differs from the other contact encoders shown herein in that pins provide the code extraction from the disc.

5.4.4 Magnetic encoders.

5.4.4.1 Background - magnetic encoders. Magnetic encoders were developed to meet the need for a device capable of accurate, reliable operation at higher rotational speeds than could be achieved using contact-type detection. Although more expensive than contact encoders, magnetic encoders do not offer substantial increase in resolution or accuracy except at high operating speeds and in systems where continuous rotation could be expected. For most applications where the combination of high shaft speed and heavy duty cycle make the contacting encoder impractical, the magnetic encoder offers an economically feasible design solution, especially where system requirements do not impose resolution or accuracy requirements beyond that normally attainable with contacting devices.

5.4.4.1.1 Detection methods. Magnetic assemblies operate by detecting resonant frequency change, a magnetization change, ***or*** magnetic saturation in an inductor. With all methods, flux induction by the magnetically coded disc affects the change by aiding or inhibiting an existing state. Thus for each principle, two normal states exist corresponding to a logical “1” or “0”. The resonant frequency method utilizes a tuned circuit, the normal frequency of which represents one logical state, and the detuning of the circuit represents the opposite logical state. In the inductance saturated method (principle of a saturable reactor), the inductor is either magnetically saturated or is nonsaturated. Alternately, the reluctance of the magnetic circuit is effectively translated to logical “1’s” and “0’s”.

5.4.4.1.2 Absolute vs. incremental. Magnetic detection methods are used in both full-word (absolute) or rate (incremental) encoders. With the full word encoder, shaft position is in a series of binary digits corresponding to the code assigned to the shaft position and a track is assigned to each digit. The code used can be any of the codes discussed herein (or others), and the rules for ambiguity logic must be followed. For polystrophic codes and single-turn encoders, dual heads are used with V-scan logic. For multi-turn or BCD codes, a combination of V-scan and U-scan are utilized as discussed in the logic section of this handbook. For incremental encoders, output is in a series of counts. As counts per revolution is determinable from design, a shaft position can be determined (± 1 count) by accumulating total counts in an electronic counter or equivalent. Up-down indication is furnished by a second sensor displaced 90 electrical degrees from the first. An electronic phase comparison determines direction of rotation by measuring phase lead and lag. Regardless of magnetic detection method, shaft position can be derived from either absolute word or incremental information.

5.4.4.2 Description. The encoder shown on Figure 12 is typical of the magnetic type unit. As indicated, the unit is similar to the brush encoders except that magnetic readout heads are used in lieu of brushes to sense disc position, the disc being magnetically coded. Encoder operation is based on a magnetic saturation principle. As in contacting encoders, the selected code is mechanized in the form of a disc attached to the rotating input shaft. The disc in a magnetic encoder is assembled using ferritic material so that when magnetized, the resulting flux pattern represents the selected code. As shown in Figure 13, each track is read by a square loop ferrite core positioned close to the surface of the coded disc. Each reading head has two windings: a primary for interrogation and a secondary for signal output l An AC signal applied to the primary induces a field in the ferrite core, saturating it in alternately opposing polarities. The square hysteresis loop of the core material induces a pulse in the secondary winding each time the field in the core switches from one polarity to the other. The input signal may be either a sinewave or intermittent pulses, as long as it consists of alternate positive and negative excursions and the amplitude and the rate of change in the excitation waveform are sufficient to change the polarity of the ferrite reading head. A strong field close to the reading head will saturate the ferrite core and cause a great reduction of the output signal at the secondary winding. Thus , the head acts as a detector of the magnetized sections of the coded disc tracks. When the head is not directly opposite a magnetized portion of the coded track, the pulses induced in the secondary winding have a relatively large amplitude representing a binary 1 signal. As the disc rotates in response to the input variable and a magnetized section of the disc lines Up with the head, the amplitude of the resulting signal induced in the secondary is quite small, representing a binary 0. Nominally, the amplitude ratio between binary 1 and binary 0 is approximately 8:1, yielding amplitude modulated pulses as the output. Interrogation frequencies in common use range from 20 kHz to 200 kHz, and encoders are produced with and without self-contained ancillary circuits for excitation and readout. Solid state or integrated circuit elements are commonly used and, in addition to providing oscillator circuits for interrogation, control networks may be included for sensor control or selective command readout.

5.4.4.3 <u>Saturable reactor and variable reluctance methods.</u> In the saturable reactor method, a magnetic readout head is placed above each track with the head axis in the normal position to the disc radius as shown on Figure 14. Physical size of a typical head is shown on Figure 15. The head is composed of the ferrite toroid and two electrical windings. One winding interrogates the core and the other is for readout of the now current magnetic state. A 20 to 1, interrogate-to-read, winding ratio is typical. Note toroid size which limits the number of heads for a given circumference. Packing density is nominally less than 20 per inch. Magnetic heads utilizing the variable reluctance principle are also used where higher resolution than that obtainable from saturable reactor heads is required. In particular, for high-speed applications, the flux amplitude switching transformer (FAST) is used. The transformer core is made from soft magnetic ingot iron which is horseshoe-shaped and has two coils. Similar to the saturable reactor head, one winding is for interrogation and one for readout. The code pattern on the drum or disc then varies the reluctance of the magnetic circuit in response to the code.

5.4.4.3.1 <u>Composition.</u> Saturable reactor heads are constructed similar to computer memory cores and have two stable magnetization states. They are made from 4-79 permalloy, 78 permalloy, or super permalloy and are toroidal in shape. Material composition differs but is basically iron, nickel, and molybdenum which is heat treated to the 1,000°C range. As such, they qualify as sintered ceramics and exhibit high permeability and coercive force, making possible bilevel magnetization with a square loop hysteresis curve. Table II illustrates the relative permeability and compositions of various materials. Of prime consideration is the coercive force of the material in use.

5.4.4.3.2 Logical “1” state. Saturable reactor heads are normally excited by a fixed frequency oscillator operating in the 20 to 300 kHz range or by an alternating-polarity pulse. The toroid core shape confines flux lines due to the interrogation voltage within the physical dimensions of the core. The core is characterized by a square loop B-H curve and two remnant states (bistable) as shown on Figure 16. Squareness ratios of 0.8 and greater are considered square. As the interrogation voltage varies, the core turnover voltage is generated and the B-H relationship is swept through the hysteresis loop. Thus, an output voltage is produced in the read winding at the interrogation frequency. The foregoing then defines one of the two logical states (logical “1”).

5.4.4.3.3 Logical “0” state. As the disc turns and a magnetic spot appears under the head, flux density is increased through induction. The core is driven into magnetic saturation along either horizontal portion of the B-H curve (WX or VU), as only two stable magnetic states are possible. The interrogation voltage is now insufficient to generate the required core turnover voltage, but swings the magnetic core state back and forth across either horizontal portion of the curve for the duration of spot influence. Thus, the AC output voltage is modulated at the rate of spot passings, generating logical “0’s”. For sinewave input, demodulation and squaring of the read voltage provides a rectangular wave corresponding to the code values of that digit. Additional processing may be performed depending on the required digital application.

5.4.4.3.4 Toroid core. The toroid core interrogate winding is usually only one turn. For optimum output a minimum of 500 milliampere turns, approximately 50 milliwatts of power, and an interrogate frequency of 20 to 40 kHz are required. Core flux densities for saturation are between 1,000 and 2,000 gausses for currently used materials and determines spot density on the coded disc. The interrogation source sees a varying impedance depending on core magnetic state. A nominal impedance is 50 to 100 ohms in the nonsaturated condition; nearly zero when saturated. Hence, excitation sources are designed to furnish large values of current into a reflected, changing impedance. Since a single source is usually used for all cores, the source must be a high impedance to avoid interdigit crosstalk. Cores are selected such that the B-H change is accomplished by domain rotation, rather than domain wall orientation. the former method requires only a change in the spin vector; thus magnetization states may be changed in as fast as 4 nanoseconds. Practical considerations limit core turnover time to 1 microsecond, an interrogation frequency of 1 mHz. To assure magnetic turnover during the linear portion of the input waveform, excitation current is normally in excess of 500 milliamperes (mA) peak-to-peak. Cores are usually made from ultra-thin annealed 4-79 molybdenum permalloy. Cores for fast switching are characterized by the well-aligned grain structure and uniform material composition.

5.4.4.3.5 Operation. All ferromagnetic materials are crystalline solids nd are composed of small (10^{-4} to 10^{-6} cm) regions called domains. Within each domain, the uncompensated electron spins have the magnetic dipole moments aligned parallel to each other by interatomic forces. No net magnetic flux density is apparent as the crystalline structure has these domains oriented randomly along the six possible 100 axes (nickel being a face-centered cubic aligns along the 111 axis). As a magnetizing force is applied, the domains align progressively from reversible boundary displacements, through irreversible boundary displacement, to saturation. At saturation, all magnetic moments are parallel with the applied field. These conditions hold approximately for all values of temperature up to the Curie temperature (approximately 450°C) at which energy of thermal agitation exceeds the interatomic forces. Without sufficient interatomic forces, the alignment within each domain is lost and a paramagnetic substance results. Thus, magnetic encoders can operate in adverse temperature environments. Interrogation voltage, frequency, and shape are not critical. Square or sine waves and even positive-negative spikes can generate core turnover, the requirement for a logical “1”. For small rates of change of excitation current, logical “1” outputs are proportional to current rate. For large current rates, the one output amplitude depends on read winding characteristics. A minimum rate of 500 mA per microsecond is required to generate logical “1” outputs independent of input waveform. A minimum peak-to-peak current of 200 mA in the normal interrogate winding will generate magnetic switching regardless of current rate. Nominal excitation voltage at the required current is in the 100 to 200 millivolt range.

5.4.4.4 Resonant frequency method. The reasonant frequency method utilizes sensors, each of which is electrically part of a series resonant circuit that is tuned to a design frequency prior to influence from the code disc. As the code disc turns, a spot appears under the sensor causing a change in the inductance of the sensor. The inductance deviation changes the resonant frequency of the tuned circuit. This change is sensed and interpreted as the opposite logical state by a frequency detector. Since the summation of spot influence at any one instant represents a unique shaft position, summation of the series resonant circuit outputs, one for each digit of the assigned code, also represents the shaft position. Depending on the assigned code, monostrophic or polystrophic, antiambiguity logic may be required. Standard lead-lag techniques are applicable. The AC excitation (oscillator frequency) is normally selected within the range of 50 to 200 kHz to obtain high level outputs, but frequencies to 1 mHz have been successfully used. Maximum interrogation rate is determined by the maximum interrogation frequency.

5.4.4.5 Design problems. Since the inherent accuracy and resolution of a magnetic encoder is no higher than that of contact types, magnetic encoders are subject to roughly the same basic quantization and instrument errors experienced in the practical manufacture of encoders using contacting sensors. Resolution is limited by the size of the magnetized spot and complicated by problems of interaction between magnetized spots on adjacent tracks. Magnetic encoders overcome the basic speed limitation of contact encoders and offer somewhat greater longevity by eliminating the need for physical contact between disc and readout device. Also, magnetic encoders have greater resistance to most natural environmental extremes and all of the standard scanning techniques can be employed. However, high ambient fluxes or radiation densities can destroy the disc pattern or inhibit saturated core operation. Therefore, greater precaution against mutual electromagnetic interference is required when magnetic encoders are included as part of a system. This requirement for additional shielding and protection to ensure that surrounding equipment does not interface with encoder operation and, conversely, that the magnetic encoder does not disturb the operation of adjacent gear, adds to the cost of an already expensive approach. Generally, the overriding design requirements that would dictate the selection of a magnetic encoder would be a need for moderate accuracy and resolution coupled with high duty cycle and rotational speed.

5.4.4.6 Neomagnetic-tuned circuit encoder. An interesting variation of the magnetic encoder is the geomagnetic tuned circuit encoder. Departing from the standard design philosophy for magnetic discs (magnetic spots in matrix fashion on a ferrite base), the geomagnetic approach uses the primary characteristics of inert metallic material. Sensors detect the presence of metal on a conventional commutator disc, and the device has the advantage of being unaffected by external magnetic fields, reducing the need for costly electromagnetic shielding. In the geomagnetic encoder the reading head is electrically connected to a series resonant circuit. When the sensor is located over a segment on the rotating disc, the resonant circuit is detuned. The decoding electronic module senses the detuned condition and converts this intelligence into binary format. sincere the segments on the disc are not magnetic, but inert materials whose only requirement is to have a different dielectric constant than air, the encoder is impervious to the error-producing effects of stray or external magnetic effects.

5.4.5 Capacitive encoders.

5.4.5.1 Backgroud - capacitive encoders. Capacitive encoders are the least used of the non-contacting types and have been developed in response to unique needs. Readout is effected electrostatically using a phase shift measuring system or a frequency control technique to develop the digital output. Although capacitive devices are not generally available as standard hardware, single turn 19-bit units have been produced in a moderately compact configuration. Another smaller encoder is available with a single turn 15-bit capability. Theoretically, the capacitive technique can be used to accomplish any of the encoding tasks performed by the contact, optical, or magnetic types. However, practical problems of design, manufacture, and operation have limited the use of capacitive detection and relatively few of these units are produced or used.

5.4.5.2 Capacitive assemblies. Capacitive assemblies provide extremely high resolution and accuracy of shaft position through electronic processing of two averaged, capacitively derived signals. Thus, capacitive assemblies usually consist of two parts, the transducer and decoding electronics. (Decoding electronics is not discussed in detail in this handbook.) As shown on Figure 17, a typical transducer is composed of one electrically grounded rotor and two insulated metal stators. Teeth are engraved on both stators and rotor, and a DC voltage is impressed on the rotor-stator combinations. A constant speed motor turns the rotor, and the input shaft turns one stator. The other stator remains fixed. With the DC voltage applied, the changing capacitance between the teeth of the moving rotor-stator combination generates two cyclic (sinewave) voltages for processing. one sinewave output is called the reference phase and represents the rotor-fixed stator movement. The other is called the variable phase and represents the rotor-movable stator (input shaft) movement. Thus, input shaft movement is represented by a pair of signals differing in phase and independent of actual rotor speed since the rotor is common to both signals. As all rotor-stator teeth affect the changing capacitance and phase, errors due to bearing runout, disc tooth manufacturing tolerances, and eccentricities are error-averaged. The signals thus generated are applied to the electronic package for processing and may be processed as rate information or as absolute position data in either binary or decimal form. The electronic package is basically a phase detector with provisions for determining direction of shaft position through missing tooth techniques, and an electronic counter and display.

5.4.5.2.1 Description. Figure 17 shows the construction of a non-contact encoder that utilizes the capacitive sensing technique. It is composed of a housing, constant speed motor, input shaft, two stators, a rotor, and a code disc. The engraved teeth on the rotor and stators generate the capacitive-derived output signal as the teeth move relative to each other. There are many methods for implementing capacitive detection, almost as many approaches as there are capacitive encoders. Since there is such a broad spectrum of possible configuration, the description presented below details a particular encoder rather than presenting the general principles common to all encoders of this type.

5.4.5.2.1.1 Detector. The heart of the capacitive encoder system shown on Figure 18 is the capacitive detector which is essentially an electrostatic tone generator. The signal generating portion of the detector consists of a grounded rotor and two insulated metal stators. Each stator has an array of 512 serrations or teeth. The rotor has two rows of 512 serrations, each matching the teeth on their corresponding stators. The detector employed in this system has one tooth removed from each stator and from each corresponding aligned row of the rotor. The rotor, driven by a constant speed motor, rotates at 600 rpm (10 rps). A +250 VDC potential applied across the stator-rotor air gap causes a capacitive output signal to be generated at a frequency of 5.12 kc, which is equal to the number of rotor teeth passing a given stator reference point in one second. A fixed zero reference point is established at the point where the missing tooth in each stator is aligned with the missing tooth in the rotor.

5.4.5.2.1.2 Stators. The reference stator is affixed to the housing of the detector. The output of this stator remains constant for any specific motor speed. The missing tooth “marked” cycle pulse in the reference phase occurs once each transducer revolution in equivalent time increments (see Figure 18). The variable phase stator is attached to, and moves with, the input shaft. As the position of the input shaft varies, the point at which the missing tooth on the movable stator aligns with the missing tooth on the rotor will also vary, causing the desired change in output.

5.4.5.2.1.3 Signals. The signals of the reference and variable outputs are in phase whenever the teeth of the two stators are in perfect alignment. If the variable stator is turned through an angle equal to a tooth pitch, the variable phase signals will shift through 360 electrical degrees with respect to the reference phase signals. Variations in rotor speed will have no effect on the phase difference between the two signals. Only a variation from zero of the angular position of the input shaft will cause a phase variation between the two signals.

5.4.5.2.1.4 Dual channel preamplifier and logic Processing circuits. The reference and variable phase information is applied to a dual channel preamplifier where the gain is increased sufficiently to overcome cable losses incurred in the transfer of the signals from the transducer to the equipment. Signals from the dual preamplifier enter reference and variable phase lock servo loops in the logic processing circuits. These signals are employed by a phase detector to control 5.24 mc oscillators. By the use of these servo loops, the outputs of the oscillators are established as precise harmonics of the basic reference and variable outputs from the detector. Accuracy through automatic frequency control is obtained by applying phaselock servo-loop techniques to a voltage-controlled oscillator, which on the other hand determines maximum angular acceleration and velocity of the input shaft for specified accuracies.

5.4.5.2.1.5 Gating circuits and secondary divider. The missing tooth signal from the detector is applied to gating circuits and a secondary divider. The secondary divider, and extension of the primary divider in the reference loop, divides the signal by a number equal to the number of serrated teeth cut on the transducer elements; in this case 512. The output of the divider is a pulse equal in frequency to the missing tooth signal and also equal to the rate of rotation of the rotor. The secondary divider is reset regularly by the reference missing tooth signal. The missing tooth signal from the variable phase channel is used to gate the registered count into an up-down counter once for each turn of the rotor or 10 times per second.

5.4.5.2.1.6 Sequence of operation. The typical capacitive encoder described above is essentially three dispersed, but interconnected, components consisting of a detector, preamplifier, and an encoder electronics chassis with an integral power supply. The detector is mechanically coupled to the measuring, tracking, or indexing equipment whose precise shaft angle is to be continuously monitored, recorded, and/or processed. Positioned within 10 cable-feet of the transducer, the dual preamplifier delivers the detector data 400 cable-feet to the encoder electronics equipment. The encoder translates the shaft angle information from the transducer into 524,288 (2^{19}) incremental counts per 360° radial turn of the input shaft. The encoder continuously provides the specific instantaneous shaft angle count (±1 count 20 accuracy) in the form of an integral 19-bit binary neon lamp display, and a 19-bit natural binary output signal for use by peripheral data processing equipment.

5.4.5.3 Inductive assemblies. Inductive assemblies are similar to capacitive assemblies in that electronic processing is required to translate the transducer output to a binary or decimal representation of shaft angle. The transducer of an inductive assembly is effectively a multiple synchro or resolver (see Figure 19). As indicated, this unit has two split stator windings displaced in space phase by 90° and a rotor. An AC voltage is applied at the reference input, and as the rotor turns in response to shaft movement, a pair of voltages representing the sine and cosine of the angular shaft movement is generated in the stator coils. Thus, the input shaft angle is transduced to a pair of voltages which may be externally processed to binary and digital indications. By utilizing many poles, the number of zero crossings of sine and cosine voltages for each revolution of the input shaft may be increased and provides an excellent source of rate information. Inductive transducers are produced with greater than 360 pole pairs, depending on allowable size and system requirements. As in capacitive assemblies, error averaging is accomplished by using the net effect of all poles. The decoder electronics must include an up-down counter, as well as the binary or digital processing and display equipment if a direction indication is desired. As with other incremental or rate data encoders, zero set and reset is an important feature.

5.4.5.4 Design problems. The number of logic processing circuits, the need for a constant-speed drive motor, the high power consumption, the lack of compactness, and the complexity of mechanical rotating components make the unit unattractive for most applications. The advantages of the unit are high count, high accuracy, and environmental resistance.

5.4.6 Optical encoder.

5.4.6.1 Background - optical encoders. An encoder detection method based on the use of optics was developed to fill the need for an encoder device of extremely high accuracy and resolution able to operate at high speed and heavy duty cycle. Optical encoders, the earliest of the non-contact devices to be developed, eliminate the wear problems inherent in contacting devices. Current optical encoders provide the highest accuracy encoding and will operate efficiently at high speeds. Although earlier optical encoders were regarded as delicate instruments, they are now highly reliable even in extreme environments. Optical encoders can be classified into three types: tachometer, incremental, and absolute.

5.4.6.1.1 Tachometer encoder. A tachometer encoder is sometimes called a single-track incremental encoder because it has only one output, which is usaly a squarewave. It senses an increment of movement, but cannot detect its direction. If movement is always in one direction, a counter can be used to accumulate a total. Velocity may be obtained by measuring the time interval between pulses or the number of pulses within a time period.

5.4.6.1.2 Incremental encoder. Optical incremental encoders may have either two or three outputs. The first two detect movement and direction; the third, called a zero reference, locates a unique position of the encoder. An algebraic counter accumulates plus or minus increments. Some counters include a quadrature-detection circuit within their electronics. Both tachometer and incremental encoders are susceptible to electrical disturbances; however, incorrect outputs can be detected by fault lights.

5.4.6.1.3 Absolute encoder. An optical absolute encoder provides a full-word output with a unique code pattern for each position. This code is derived from independent tracks on the disc corresponding to individual photodetectors. A high or low output could be obtained depending on the code disc pattern. This one-to-one correspondence renders the encoder immune to power loss. Errors caused by electrical noise will only last for the duration of the noise.

5.4.6.2 Description. In an optical encoder (see Figure 20), the tracks on the disc consist of transparent and opaque segments produced by exposing a photographic emulsion to light. The emulsion is usually mounted on a glass disc to provide mechanical integrity and dimensional stability. Where greater durability is required, metal may be plated to the glass. Readout is effected by an array of carefully aligned photoelectric transducers positioned in front of the disc. A light source behind the disc provides excitation. As the disc rotates in response to the input variable, the opaque areas on the disc pass between the light source and the sensors, interrupting the light beam and modulating the transducer output in accordance with the selected code and as a function of the input variable. A slit or a lens system, placed between the disc and the photocells, serves to focus the light and make the readout more exact. Light focusing in an optical encoder is similar to sensor width in a contacting encoder or flux density in a magnetic device. The photocells are positioned to read out the various tracks of the disc pattern. The configuration of a typical optical encoder is shown on Figure 21, and illustrates a non-contact encoder that utilizes an optical sensing technique. It is composed of a lightproof housing, a Precision coded disc made from glass, an electronics board, a source of illumination, a mask, and a multiple photosensor detector assembly.

5.4.6.3 Optical systems. Optical systems are used to guide or focus light on the coded disc or light sensor when required. Mirrors, prisms, lenses, fiber optics and optic slits or diffraction gratings perform this function. Of particular interest is the newer fiber optic technique. Fiber optic techniques may be used when identical optical paths are required, such as in a pair of differentially read light sensors. Fiber optics are light pipes which are used to guide light from the source to the readout station. They are composed of glass fibers made into bundles and operate on the principle of total internal reflection, such that light imposed at the end of one fiber appears at the other end by multiple reflections through the fiber length. By using identical length fibers for any pair of sensors, identical optical paths are formed, stabilizing phase relationships. Leakage of light from one fiber to another, which would cause erroneous encoder output (crosstalk) and low light transmission efficiency, is reduced by coating the fiber with a glass having a different and lower index of refraction. The coating process is called cladding and indices of refraction for the fiber and cladding usually differ by nearly 0.1, 1.62 and 1.52 being typical, respectively. Transmission light efficiency is greater than 80 percent for the fiber lengths used in encoders. (A common mirror has an efficiency of approximately 80 percent.) Light gathering ability varies as the square of numerical aperture. Numerical aperture is defined as the sine of the angle whose value is the square root of the difference of the squares of the individual indices of refraction.

5.4.6.4 Light detection. As shown on Figure 22, light detection can be performed by one of several devices. Material for all types of light detecting devices are selected from Groups III, IV and V of the periodic chart and lie halfway in the chemical spectrum between metals and nonmetals. As such they are semiconductors. Each device indicated responds to light in a different manner. Photovoltaic cells, such as selenium or silicon, generate an electric current when exposed to light. Photoconductive cells, on the other hand, have a varying resistance to the passage of electric current with varying light intensities. Such cells are usually made from cadmium sulphide or cadmium selenide, depending on required response time or the portion of the light spectrum for which sensitivity is desired. Current capability varies with the quantity of incident light. Photodiodes are similar to photoconductive cells, except that the photodiodes allow electrical current flow in only one direction when exposed to light (diode rectifier action). Phototransistors are photocells with built-in transistor amplification. Silicon-controlled rectifiers (SCR's) act as sensitive high-current switches when exposed to light.

5.4.6.5 Optical assemblies. Figure 22 illustrates various components used for optical detection of coded disc patterns. The methods shown are representative of typical optical encoders.

5.4.6.6 Light sources. Light sources for optical encoders may be incandescent, glow discharge, or solid state depending on the application or economy required by the system.

5.4.6.6.1 Incandescent lamps. Incandescent lamps are used where continuous illumination (incremental or rate information encoders), high life, and low-failure rate are required, and where low peak illumination is tolerable. Single or multiple lamp arrays are used with a trend toward the latter to avoid the long, thin bulb filament required to cover the photo-sensing area. A stiff, lightweight filament is obtained in the multiple lamp, miniature bulb array by using a helical filament configuration. In this manner, bulb life under adverse conditions of shock and vibration is lengthened, allowing nonreplaceable bulb assemblies to be permanently mounted within the encoder. Typical bulbs are 0.12 inch in diameter and 0.14 inch long, and may have a built-in focusing lens. By placing the lamp assemblies closer to the disc, a reduction in the illumination requirements is obtained, allowing a reduction in electrical excitation. The net result in terms of lamp life is illustrated on Figure 23. Power requirement is in the 500 milliwatt region. Normal lamp life is 5,000 hours when operated at rated voltage, with random failure rates of 0.1 percent per 1,000 hours of operation. As indicated, lamp life approaches encoder life in a voltage-derated, surge-protected miniature lamp array.

5.4.6.6.2 Glow discharge lamps. Glow discharge lamps such as the xenon flash tube or strobe lamp are used as sources where high peak luminescence is required (Gray code encoders). Glow discharge type lamps are pulsed to reduce average power requirements, the triggering normally being accomplished by a 10-volt, or higher, trigger pulse. Power requirements for lamp firing vary, but are in the range of 600 volts at 30 mA peak. Capacitive discharge networks are required. Minimum light duration determines the maximum angular encoder speed for a nonambiguous output for any given encoder resolution (number of binary digits read out). Thus, for a 10 microsecond illumination in a 10,000 count encoder, a maximum speed of 600 rpm can be used. Flash tube life varies from 500 to 5,000 hours depending on interrogation rate. Life is usually limited by gas and electrode contamination and is directly proportional to interrogation rate which is nominally 50 pulses per second. Radio frequency interference (RFI) and encoder noise are proportional to the peak energy required for illumination (0.03 joule peak). Consequently, glow discharge type lamps and power leads normally require a filter system in critical noise applications. (Refer to MIL-STD-462 for noise reduction requirements and MIL-STD-461 for RFI test methods for usage on military airborne equipment.)

5.4.6.6.3 Solid-state light sources. Solid-state light sources are also utilized in optical encoders in lieu of incandescent or glow discharge lamps. These devices are characterized by extremely long life, excellent shock recovery in excess of 100 G’s, but reduced total luminescence when compared to the incandescent bulb. Relative response to light frequency of various light-sensitive devices is shown on Figure 24. One solid-state light source is the gallium arsenide diode developed through experiments with laser (light amplification by stimulated emission of radiation) techniques. Additional solid-state semiconductor data was obtained in a material study for solar cells (see Figure 25). At -196°C, the gallium arsenide diode can produce coherent (parallel) beams of light when injected with sufficient current (20,000 amperes per square centimeter). Between -65° and 125°C the material is fluorescent and emits noncoherent light in the infrared region at 8,400 angstroms. Spectral width of the emission is approximately 150 angstroms and is of low intensity. Aperture of the light emission ranges from 60° to 180°C. By using a silicon detector which has a light resonance or peak sensitivity in the same spectral region (see Figure 26), usable outputs are readily obtainable. Output frequency varies with the forward current. Modulation of the gallium arsenide diode can be accomplished linearly by deviation for forward bias currents at rates from DC to 900 mHz. Silicon carbide also exhibits similar characteristics, both materials being state of the art. Typical gallium arsenide diodes are 0.0591 inch in diameter and 0.11805 inch long when combined with a lens system. Lens systems are used to collimate the light into a coherent emission. The diodes are formed by combining liquid gallium at 30°C and arsenic vapor at 1,240°C, then coding to obtain a single N-type crystal. Slicing the crystal and lapping with a P-type material such as zinc completes the P-N junction. As a detector, a typical diode with incident energy (solar cell applications) of 100 milliwatts per square centimeter will produce up to 0.9 volt at 23 mA per square centimeter of junction area. As a light source, diode power requirements are in the 50 milliwatt range for usable outputs, and are usually obtained from a constant current source to enhance stability of output wavelength and current. Gallium arsenide is also temperature sensitive, but when combined with the temperature characteristics of the silicon photosensor, a relatively linear temperature output current results as shown on Figure 27. Theoretical temperature limitations based on the wide electron band gap indicate usability to above 400°C. Effects of aging diodes by constant forward mode injection currents in the 100 mA range as a function of time and temperature are shown on Figure 28. An apparent maximum decrease in light output, worst case, is 73 percent for 10,000 hours aging, high temperature, high current inputs. Relatively linear light output curves are possible. The gallium arsenide diode has a high atomic weight and low minority carrier lifetime and thus shows excellent radiation resistance. The calculated electron threshold energy for Frenkel defects in the material is 270 kilo-electron Since the gallium arsenide diode and associated elements show promise in difficult encoder applications, the material characteristics relative to common semiconductors and near semiconductors are listed in Tables III and IV.

5.4.5.5.4 <u>PN silicon photovoltaic cell.</u> For encoder usage, the PN silicon photovoltaic cell is in extensive use for fast and great response in the 9,000 Angstrom range. On-off output ratios of greater than 8 to 1 are obtained. Silicon cells range in size from 1.25 inch diameter circles to 0.005 by 0.015 inch for the rectangular form. The blue-black positive face of the crystal is light sensitive. Cells are usually supplied in groups with a beryllium copper mask to eliminate cell interaction (crosstalk). One side of the mask may be coated. Mask thickness is nominally 0.002 inch. Silicon photocells are temperature sensitive and, over normal operation ranges, may change 35 percent in output under the same illumination. Temperature compensation may be obtained through selection of an opposite characteristic light source or by thermistor compensation of the photocell itself.

5.4.6.7 <u>Design problems.</u> In optical encoders the limitations of contact or sensor size are removed, and much higher accuracy and resolution are attainable. Disc patterns, produced photographically, can yield segments as fine and as exact as 0.0005 inch. The light source is usually a miniature tungsten filament bulb or a solid state device, such as a gallium arsenide or gallium arsenide phosphide light source producing excitation in the infrared region. Either approach yields substantial reliability.

5.4.6.7.1 <u>Signal-to-noise ratio.</u> Much of the accuracy and resolution that can be achieved with optical encoders depends on precision focusing of the light beam. The filament bulb and slit method is adequate for most applications; however, solid state light sources are available with integral lens systems which provide a dramatic improvement in signal-to-noise ratio, a factor affecting overall encoder performance.

5.4.6.7.2 Precision bearings required. Because of the potential accuracy of the detection method, higher accuracy and precision is required in the design and manufacture of optical encoder bearing assemblies. Regardless of the precision used in producing the disc, eccentricity will be introduced by an inferior bearing assembly since eccentricity errors result from misalignment between the center of the disc pattern and the axis of rotation.

5.4.6.7.3 Accuracy. The major items that limit resolution in an optical encoder are the wave length of the light source, the fineness of the segments in the disc pattern, and the overall accuracy of the encoder system. At present the crucial factor is overall system accuracy. Discs and light sources are currently available which are capable of a level of precision in excess of that required due to mechanical and electronic errors produced in the rest of the encoder. Many of the logic processing circuits used with contact encoders are, by their nature, unsuitable for optical devices. For this reason antiambiguity is implemented in optical encoders through the use of non-ambiguous codes which often require output processing to put them in natural binary or some other directly usable form.

5.4.6.7.4 Cost. Generally, the optical encoders are the most expensive, the most sensitive, and provide the highest performance levels. When first developed, the optical encoder could not withstand extremes in operating environment; however, there has been much improvement in this area in recent years. Optical encoders are best applied in situations where high speed, extended service life, accuracy, and resolution are mandatory, thus justifying the increased cost.

5.4.7 Special devices.

5.4.7.1 Background - special devices. For special or unique applications, variations on the basic encoder types have been produced. In a number of cases the basic techniques have been combined or modified to capitalize on their several advantages and minimize the theoretical limitations. In this section a number of these special or unique system approaches are described and discussed.

5.4.7.2 Energy coupled encoder. A recent investigation of error sources in encoders has shown that perfect shaft alignment and concentricity in Moire fringe devices is not possible. A new device, the energy coupled or shaftless encoder shown on Figure 29, has been developed. The illuminated reticle is located in the object plane of the lens, and the lens and reticle are aligned approximately on the longitudinal axis of the rotating shaft to be measured and encoded. The focused image of the reticle is directed along the axis via the lens. Affixed to the end of the shaft to be measured is a simple 45° prism. Prism tolerances not being critical, the focused light is deflected 90° from the original axis and the image of the reticle is focused at a point in space. Located about the axis is a cylinder bearing an annularly disposed (ring-like) incremental information track. The internal radius of the cylinder lies in the image plane of the lens. Any rotational movement of the shaft and its 45° prism causes a precisely similar movement of the image of the reticle projected on the inner curvature of the cylinder. The coded information track consists of a series of small mirrors which alternately absorb and reflect the image of the object reticle in much the same manner that movement is detected in more conventional devices.

5.4.7.2.1 Example. The object reticle may be, for example, a small circular aperture so long as the reticle image is equal in diameter to one-half the pitch of the lines on the information track. The light which is reflected from the mirrored segments on the information track traverses the original path and an image of the object reticle comes into focus at the original object plane. Interposed in this return path is a beam splitter which directs a portion of the reflected light to the collecting lens. The collecting lens directs the light to the sensitive surface of a photo-transducer. The resulting electrical output is used as in conventional encoder devices.

5.4.7.2.2 Accuracy. A much higher degree of overall accuracy can be achieved with an energy coupled encoder since the inherent inaccuracies of mechanical assemblies (shafts, bearings, brushes, and so on) are eliminated. Further, the expected reduction in accuracy resulting from normal mechanical wear is also avoided. However, the complexity of the device carries a substantial penalty in expected service life and reliability, and the resistance to environmental extremes is quite limited.

5.4.7.3 Servo-encoder modules. A typical example of an encoder combination device is the servo-encoder module, developed to provide a modular subsystem which the system engineer can consider as a component with the capability of fulfilling the common functional needs in navigation systems. These units have an electrical input and a digital output and, therefore, can eliminate many problems that arise in retrofitting digital capabilities into existing systems. While designed to achieve low production costs, their structure permits simple prototype modifications and the use of a variety of encoders. Standard cordwood circuits such as encoder drive circuit, output logic level clamping, lock-up circuits, line drivers, and interbit amplifiers can be incorporated in the modules to accommodate various interface requirements. Typical production units utilizing binary-coded decimal (BCD) encoders are shown on Figure 30 and are described below.

5.4.7.3.1 Latitude module. The latitude module accepts a one and twenty-five speed 26V, 400 cycle synchro input and provides a parallel 8-4-2-1 code binary decimal digital output. The encoder used is a standard BCD unit which generates the latitude function, complete with sign, in degrees and hundredths of degrees.

5.4.7.3.2 Longitude module. The longitude module is identical with the latitude module except for the encoder which provides a parallel, unambiguous digital output of longitude in degrees and hundredths of degrees, complete with sign, in 8-4-2-1 binary decimal code.

5.4.7.3.3 Altitude module. A one and twenty-five speed synchro input is also required for the altitude module. Output is parallel 8-4-2-1 binary decimal code, obtained from a standard BCD encoder. Total altitude range is 100,000 feet with 10 feet being represented by each bit of the encoder output .

5.4.7.3.4 True heading module. The true heading module receives heading information via a single speed synchro input and converts it to digital form. The encoder output provides degrees and tenths of degrees in parallel, unambiguous 8-4-2-1 binary decimal code.

5.4.7.3.5 Ground speed module. A BCD encoder is used in the ground speed module to provide a digital output from the single speed synchro input. The 8-4-2-1 BCD code output provides ground speed information at one knot per bit.

5.4.8 Comparisons and summaries - encoders.

5.4.8.1 Basic considerations - error factors. To evaluate the relative merits of an encoder for a particular application, it is necessary to understand some of the chronic accuracy and design problems and how they are solved. To specify encoder accuracy, the first requirement is to define and identify two basic inherent error factors: quantization and instrument.

5.4.8.1.1 Quantization errors. Quantization error is fundamental to all digital equipment because of the quantum nature of digital codes. In a perfect encoder with no mechanical, optical or electronic deviation from the ideal, the mean angular position of the input shaft for a given readout is defined as the angular position midway between the transition from the next error readout to the transition for the next higher valued readout. The quantization error is the deviation of the input shaft from the mean position for a given readout with the maximum error ±0.5 of the angular rotation between two successive bits. For a 16-bit encoder (one containing 2^{16} or 65, 536 bits per revolution) the angle per division is 19.78 seconds of arc; the maximum quantization error is therefore about 10 seconds of arc. Table V lists the bit count (as powers of 2) most likely to be encountered in state-of-the-art encoders and correlates this data to the corresponding segments per turn and angular equivalent.

5.4.8.1.2 Instrument errors. Instrument error is introduced by the actual manufacturing and assembly process and is defined as the difference between the shaft angle as indicated by the encoder and the actual shaft angle at the midpoint of the given readout. Most manufacturers limit this error to about the same magnitude as the quantization error. The instrument data sheet, normally available for an encoder, will list the specified instrument error; however, in applications involving a large number of readouts, a statistical specification of encoded error is more significant. The standard quantization error combined with the standard deviation of instrument error produces the standard deviation of total encoder error. This figure is generally less than quantization error alone, but is determined by individual manufacturers for each product. One of the most desirable design goals for encoders is to have as many bits per track as possible to increase the resolution. One method increases the size of the encoder, but this soon runs into problems of compatibility with system envelopes, vibration, shock and temperature limitations. A standard solution has been to install gear trains between the primary disc in the encoder and subsequent fine reading discs. In this way, the fine increments can be read in much the same fashion as the second hand on an alarm clock. However, the resolution on the fine increments is still no more accurate than the primary disc and is further decreased by the inaccuracies inherent in any gear train. The most recent trend improves the techniques of reading finer lines on a disc of reasonable size. There are direct reading encoders available from a number of manufacturers in the 19-bit range. Another design parameter, the least significant digit (LSD), generally located on the outermost track, is defined by the following relationship:

$$\mathrm{LSD} = 360°/2^N$$

where N equals the total number of binary digits on the track.

To find the most significant digit (MSD) on the innermost track:

$$\mathrm{MSD} = 2^{N-1}\,(360°/2^N)$$

On Figure 8, brush B_0 reads the LSD and B_3 the MSD.

5.4.8.2 Contacting vs. non-contacting encoders. Brushes are usually made from gold-alloy wire in groups, 5 to 10 wires per group, to allow redundant operation. A typical 6-strand brush and brush assembly are shown on Figure 31. As illustrated, each wire is crimped identically to the other five as they must rest on exactly the same disc readout area. Final positioning and soldering of brushes is performed under optical magnification. A completed brush assembly nominally requires a 0.004 inch disc contact area, with brush deflections due to contact pressure of 0.010 to 0.050 inch. Brush construction requires a memory removal technique to eliminate the tendency of wire to regain its original configuration. Brush assemblies can typically maintain a contact area within 0.004 inch of original positioning after shaping in this fashion. Brush tension is maintained by a rigid polycarbonate brush holder and stabilizer assembly. Material selection of the total assembly is chosen to eliminate resonances which would allow brush bounce during vibratory motions. Total brush contact force is nominally divided between the brush stabilizer and brush operating against the rigid holder. Elimination of brush-disc lubrication is accomplished by careful selection of materials.

5.4.8.2.1 Problems in contacting encoders. Perhaps the most serious problems arise in contacting-type disc pattern encoders as a result of variations in contact, or more specifically, in brush alignment. Brushes are susceptible to vibration and acceleration forces, which can cause intermittent contacts and shifts in brush position. Since shaft friction, resistance to mechanical disturbance, and operating life all are functions of the brush pressure, a compromise must be made among them in the design of an encoder. Resistance to mechanical forces can, in general, only be obtained at the expense of increased friction and lowered operating life. Also, it is difficult to fabricate multiple-brush assemblies for reflected binary commutator codes with sufficient built-in accuracy, and adjusting screws are usually provided so that the brushes may be individually adjusted during the final tests of the encoder (see Figure 32). Brush alignment, therefore, is a problem not only in the original manufacture of commutator encoders, but a continuing problem as vibration and brush wear tend to move the brushes from their original positions. One quantum in a three-inch diameter, 10-digit code disc is about 0.010 inch, and a typical brush width is about 0.005 inch. Brushes must be positioned within about 0.002 inch if any allowance is to be made for the contributions to equivalent brush width of pattern errors and shaft eccentricity. Considerable improvement is possible through the use of pin contacts as the sensing element, in place of the lower cost, lower performance brush assembly. However, of necessity, these must be improvements in degree rather than in kind.

5.4.8.2.2 Problems in non-contacting encoders. Most of the above problems are minimized, if not eliminated, in non-contacting encoders, especially of the optical type. Since there are no rubbing contacts, there is no contact wear problem and no contact-imposed limit on the disc life or disc operating speed. The photocell assembly and optical slip can be made more rigid than the brushes of the contacting encoder, and slits can be made extremely straight and of constant width by using a ruling engine.

5.4.8.2.2.1 Small slit alignment tolerances. The problem of relative slit alignment between zones is, therefore, not troublesome in optical encoders, except that the reduced dimensions of the segments make the tolerances on slit alignment very small. For example, in a typical 13-digit reflected binary encoder with a 2.75 inch diameter disc, a segment on the 13th zone is 0.0018 inch wide, and a quantum is 0.0009 inch wide. The 0.0006 inch reading slit must be radial with a tolerance of 0.0001 inch and must be of constant width within the same tolerance.

5.4.8.2.2.2 Cell output. Another problem in optical encoders arises because of the finite width of the slit and the optical diffraction effects. The cell output does not change abruptly from dark to light as the disc moves. To detect the exact position of a transition in the pattern, an external amplitude discriminator is required at the cell output, and variations in the discrimination level add to the equivalent brush width.

5.4.8.2.2.3 Reading system complications. Despite the advantages of optical encoders with respect to reading resolutions and accuracy, the optical encoder has some new problems of its own. The reading system is more complicated than a commutator and brush system and is perhaps just as likely to give trouble, although for different reasons. Disc may be read either by flashing the light or by using a steady light and turning the photocells on and off. If a flash lamp (usually xenon) is used, the encoder requires a high voltage power supply which may be troublesome in some applications. Also, cell outputs with flash excitation are so small that an amplifier is required in each cell output, and gain stability is required to maintain a small discrimination band. If a steady light is used, cell output can be improved, but the discrimination circuits must now be able to distinguish a light cell from a dark one under all conditions. Two methods for doing this are to use cells with no dark output (for example, cadmium selenide), or bridge detector circuits to suppress any dark output from the cells.

5.4.8.3 Summary - contacting and non-contacting encoders. Shaft encoders can be considered in two categories: contacting encoders and non-contacting encoders. The contacting encoders are generally the least expensive and the most popular. But they are limited in their applications because of limited accuracy, life characteristics, and operating requirements. The non-contacting encoders are generally more expensive but offer greater accuracy, reliability, and in general will withstand more severe operating requirements. Contacting encoders consist almost entirely of brush types and pin contact types. The non-contacting encoders include those utilizing magnetic, optical and capacitive techniques. Various techniques of encoder implementation are used to increase reliability and accuracy.

5.5 Construction of encoders.

5.5.1 Size, shape and performance.

5.5.1.1 Design considerations. The size and shape of an encoder is usually limited by the space available within the parent system. The size and shape of the encoder, in turn, exert a profound influence on overall encoder performance. The primary performance factors that are most directly related to the size and shape of the unit are resolution (counts per turn), total output counts, coding technique, and transition accuracy. A wide variety of standard encoders is available with an equally broad spectrum of performance levels. In addition, new devices are developed each day for special applications, thus increasing the range of design possibilities. New encoders, developed in response to new system demands, continue to demonstrate the interrelationship between mechanical arrangement and performance. Size and shape versus performance are interdependent variables in encoder design which require system decisions and compromises to derive the optimum combination for a given encoding task. In some cases encoder performance is a primary consideration and some latitude in packaging is permitted; at other times the allotted envelope and weight are fixed and performance must be optimized within those limits. However, much of the progress in encoder design has resulted from the most demanding design conditions where a fixed level of encoder performance must be packed into a restricted area, of a certain shape, and within rigorous weight limits.

5.5.1.2 Standard shapes and sizes. The central components in an encoder are rotating components; therefore, the universal shape for encoders is some variation of a basic cylinder. Some typical encoder outlines and dimensions are shown on Figures 33 through 40. Due to the similarity in the shape of encoders and synchros, encoder size is usually expressed using the standard synchro mount size system which is based on the outside diameter of the case in inches to the nearest 0.1 inch. An encoder packaged in a case with an outside diameter of 3.5 inches is referred to as a Size 35. Similarly, an encoder identified as Size 23 has an outside diameter of 2.3 inches (±0.05 inch). This sizing system does not account for encoder length, which is a function of the number of internal stages and such external features as connector accommodations, headers, or cabling provisions. Typical encoders resemble synchros. By size, they are classified according to diameter in tenths of an inch and vary in diameter from less than 1 inch to over 12 inches. All types may contain multiple geared discs where digit output is not consistent with single disc construction. Encoder length varies with the number of discs required to generate the specified binary output and other system requirements.

5.5.1.3 Performance parameters of size. The degree of encoder miniaturization that can be achieved within current manufacturing tolerances is summarized in Table VI, which lists some typical encoder performance levels and shows the approximate required minimum package diameter. The minimum sizes shown in Table VI will provide sufficient transition accuracy to ensure that every number appears in correct sequence throughout the life of the encoder. Table VI lists theoretical minimums, and encoders of these sizes may not be immediately available as shelf hardware, although encoders of the size and performance levels shown in Table VI could be produced. Cost is another important criterion of system performance that is influenced by encoder size. In general, cost is an indirect function of miniaturization so that a moderate compromise in minimum dimension can result in a substantial cost advantage. With moderately sized encoders, manufacturing tolerances are less severe. It is more likely that a larger unit will be available as a standard, mass produced item with all of the attendant economies.

5.5.2 Structural design and housing.

5.5.2.1 General design. To understand encoder operation, it is helpful to know something of the details of encoder construction. As rotating shaft components, encoders function effectively as a high-precision rotary switch. To accomplish this, a coded disc is mounted on the rotating input shaft which, in turn, is supported on instrument quality bearings. The encoder is enclosed in a cylindrical case or housing which protects the internal works and provides a mounting and support surface for the detection mechanism, ancillary circuits, and bearing assemblies. In contact or magnetic devices, the lamp and photocell assemblies are replaced with brush or contact blocks or an array of magnetic readout heads, respectively. In capacitive encoders, the mechanical design and packaging requirement is substantially more complex as the housing must enclose a precision excitation motor and the rotor and stator assemblies. Since encoders are precision instruments, design restraints and manufacturing tolerances are extremely demanding and are a primary factor in performance, accuracy, service life, and reliability. The ruggedness and structural integrity of the internal and external mounting arrangements determine resistance to extremes in operating and environmental ambients. Bearing quality and design and the alignment and arrangement of rotating elements (disc, shaft, and so on) determine the overall instrument error due to eccentricity and other alignment factors. The mechanical design of contact sensors, the mounting technique, and contact pressure determine the wear characteristics of the unit.

5.5.2.2 Housings. Housings for encoders are made of steel, titanium, or aluminum, depending on the application, and to equivalent tolerances of the bearings, disc, and sensor components. The housing is composed of end frames and a cover. Encoder front frames are particularly critical to dimensional tolerances as input shaft perpendicularity affects encoder life, reliability, and accuracy. The rear frame usually contains the electrical connector or a method of wire feedthrough. The encoder case or enclosure must provide protection and ruggedness in proportion to the demands of the application. Encoders used in airborne, surface, or mobile equipment require more protection than units designed for indoor or static use. Generally, the encoder case is constructed of anodized aluminum, stainless steel or other corrosion-resistant material, and is designed to exclude dust, moisture, and foreign materials. The case must be sufficiently sturdy to withstand adverse operating conditions and large enough to enclose all components requiring protection. At the same time, the case must not add undue bulk or weight to the overall unit. An encoder housing must also provide access to the electrical output of the unit. In some units this is accomplished by an insulated terminal block or integral receptacle designed to mate with a cable-mounted connector. In other units the electrical output is available on pigtail leads brought out from inside the encoder. The enclosure must be designed for physical interface with the parent equipment. This requirement includes mounting, electrical connections, and input coupling.

5.5.2.3 Bearings.

5.5.2.3.1 Accuracy. The design and selection of encoder bearings are extremely important to overall accuracy, as well as being a critical factor in service life and reliability. Encoder discs are manufactured to extremely fine tolerances, often using chemical milling or photographic processes accurate to 0.0005 inch. Since the disc rotates on a shaft, the usable accuracy of the disc can be no better than the quality of the bearing will permit.

5.5.2.3.2 Radial and end play. Encoder bearings must be designed and selected for minimum radial play and end play commensurate with the accuracy of the disc pattern. Lubrication, an important factor in bearing life, should be of the permanently sealed type to ensure that oil and grease are not introduced into the encoder. Radial and axial load must be carefully matched to the needs of the unit, taking into consideration such factors as torque, gearing, speed, and size.

5.5.2.3.3 Quality. The bearings used in encoders determine ultimate encoder life. In critical applications, bearing pairs matched for total internal runout are hand selected. Bearings are required to induce uniform, low starting and running torques, and simultaneously reduce radial and end play to a minimum. Only high quality instrument-type bearings are used for encoders. Most encoder bearings are manufactured to high tolerance levels (ABEC classes 5, 7, or 9; see Table VII) and are of the radial retainer type (Conrad). Typical bearing tolerance for squareness, parallelism, and runout for unselected bearings approaches 100 microinches, thus limiting minimum bit size on a disc. Due to the fact that torque increases caused by corrosion and contamination are the major cause of bearing failure and not failure due to load, encoder bearings are normally made from AISI 440 C stainless steel, or SAE 52100 chrome steel for heavy loadings. These materials exhibit a Rockwell C hardness of 58-63 to 60-65 and a temperature range from -100° to +300°F while still maintaining dimensional stability. Retainers for the bearings vary with encoder application. The crown retainer is most used for instrument type bearings and is precision stamped from hardened 410 stainless steel and has coined ball pockets. The crown retainer has good wear and excellent low-to-high speed torque characteristics. Where extremely low starting torque in low-speed applications is required, the ribbon retainer made from soft 430 stainless steel may be utilized. Where high-speed operation at less than 250°F is required and is more important than low-speed torque, machined retainers of phenolic laminated plastics are used. This type usually requires external lubrication for long life. Shields may be used with most bearings to reduce contamination from wear particles or excessive pressures.

5.5.2.3.4 Lubrication. Lubrication of encoder bearings is the most important factor in bearing and encoder life. Tested lubricants for normal environments are available and a standard bearing life can be determined. These include oils, greases, silicons, and dry films. As lubrication film thickness is critical, dry film usage is restricted. Normal lubrication thickness varies, but should be between 0.0001 and 0.0003 inch, with variations over a single bearing limited to approximately 10 microinches. Variations in lubrication thickness during manufacture are limited by a centrifuge technique after initial lubrication. To indicate state-of-the-art considerations in encoder bearing design, the problems of adverse environment as they affect lubricants are discussed in the section covering selection of an encoder.

5.5.2.4 Coded discs. The most critical part of an encoder is the coded disc (or drum) and the greatest of care is used in manufacture. Disc accuracy and mounting usually determine the maximum possible basic accuracy obtainable from an encoder if other encoder parts are selected with the equivalent care. The required number of tracks (digits) determines disc and encoder size. Current manufacturing techniques establish the minimum size and accuracy to which the least significant digit can be placed on a track, limiting disc diameter. Where digit and diameter requirements preclude manufacture of a single disc, multiple discs with gearing are used. Typical gear ratios range from 10-to-l to 100-to-1, with 32 and 64 being common ratios.

5.5.2.4.1 Full word disc description. To illustrate construction of a disc, the manufacture of a typical brush type, full word (absolute) binary disc is described. A full word disc gives all digits representing shaft position for each interrogation. These discs are made by a series of steps that utilize the economy and accuracy of photoreduction. First, design computations for all counts of each track are laid out on an oversize master pattern. Disc tracks are concentric with the disc axis, each track representing the states of a binary digit as shown on Figure 41. The least significant digit (LSD) is located on the outermost track (largest circumference) and the most significant digit (MSD) on the innermost track. The most significant digit track has conducting and nonconducting segments of 180°. The least significant digit track segments may be as small as 72 microinches for some types of discs; brush type disc least significant digit segments being less than 0.010 inch in length. Segment accuracy to 0.004 inch is maintained for brush discs produced by photoetching. In any case, the least significant digit track has an angular span related to 360° divided by 2^N, where N equals the number of digits on the disc. The master pattern is photographically reduced to actual size using precision optics and developed on a photosensitive material. The material is then gold plated to form a gold image of the master pattern with impurities induced for better wear characteristics. Next, the image is stripped from the backing, applied to an aluminum panel, and cured under pressure. After curing, precision machinery bores the center shaft hole, dresses the outer disc diameter in some cases to eccentricities of 0.00003 inch, and press fits the input shaft into a hub which was turned on the reverse side. For some discs, shaft fits are made under optical magnification offsetting the shaft axis to compensate for disc eccentricity. Hole filling is accomplished with epoxy. This process is a form of error averaging. Shaft-disc perpendicularity must be within bearing runout tolerances to avoid additional error in code sensing for nonerror-averaging code-sensing techniques. Other methods of creating disc patterns and other materials are used for encoders depending on the code-sensing method. Disc material may be plastic, glass, rhodium-plated glass epoxy, phenolic, or sintered ceramics. Extremely high disc pattern accuracy may be obtained by the circle dividing engine programmed by a computer. Resulting disc segment positioned accuracies of 0.5 second of circular arc, or approximately one part in 4,000,000 are possible on some types of discs. For magnetic discs, a barium ferrite ($BaFe_{12}0_{1}9$) is usually used as the disc blank due to its high coercive force characteristic (1,600 oersteds). These discs have a preferred sense of magnetization parallel to the axis of the disc created during manufacture. Upon magnetization, the crystal structure is permanently aligned to the desired code pattern. Both sides of the disc are usually used with, nominally, four tracks per side representing a resolving dimension of 0.033 inch. Magnetic spots are created on the blank by magnetic writing or by creating raised patterns (braille technique) with ultrasonic machining. Optical disc encoder material varies from precision-ground optical glass to plastics for high-shock, economical discs. Glass disc thickness is nominally held to no less than 0.143 the disc diameter, yielding 0.5-inch discs in large diameter encoders. Flatness requirements are determined by the wavelength of the light source-sensor method, 9,000-Angstrom sources being typical, and the nearness of sensors to the disc. Polishing of discs to one wavelength flatness is accomplished. Minimum sensor-disc spacing is preferable, but is limited by disc wobble caused primarily by bearing runout, end play, and disc-shaft perpendicularity. Rulings on a glass disc can be accurate positionally to less than 0.2 second of arc with bit widths of 72 microinches. Discs for 2^{16}, or one part in 65,536, are nominally 0.0002 inch for an 8-inch diameter encoder. Disc-shaft mounting and flatness techniques hold disc wobble to well within 0.0005 inch for high resolution, small diameter encoders (2^{13}, size 11, multi-turn encoder). Discs for capacitive units are usually required in pairs. The discs have no code tracks as previously described (except for conversion to decimal) but have a row of teeth engraved on the periphery. The changing capacitance between the discs as one disc turns generates an averaged phase output proportional to input shaft rotation. Similarly, discs for inductive units are required in pairs and consist of metallic deposits on insulated plates in the shape of hairpin turns. Each turn is called a pole and greater than 360 poles can be placed on each disc. The discs are inductively coupled and produce sine-cosine voltages corresponding to the input angular position.

5.5.2.4.2 Incremental rate sensing disc. Discs previously described have tracks concentric with the input shaft and are full word (absolute) discs. Shaft position may also be sensed with incremental rate information. One such method is the sensing of a moire fringe pattern originating from two ruled discs (see Figure 42). These discs are used in high resolution optical encoders. One disc is fixed while the second turns with the input shaft. One disc has N lines and the other, N+1 lines, which creates an interference pattern of light intensity for the sensors. Lines (rulings) are placed on the disc with an accuracy to one arc second using photoreduction. The total number of rulings is usually held to 1,024 and below for standard encoders. Sensing of position through rate information is discussed in another section of the handbook.

5.5.2.4.3 Inductive sensing discs. Discs for inductive sensing of shaft position (Figure 43) are similar to incremental or capacitive discs in that two discs are required. The inductive disc is formed by depositing metal in the form of hairpin inductors on an insulating disc. Each deposit is called a pole and division of shaft angle is proportional to the number of poles. Discs are made with up to 360 poles in common encoder sizes. As for the incremental disc, outputs differ in phase, the principles of which are discussed later in the handbook.

5.5.2.5 Multi-turn units and gearing. Multi-turn units with gearing or multiple discs are used to increase count capability (resolution) when disc manufacturing capability cannot produce a disc with sufficient bits in the given diameter. Encoders of medium to small size may be multi-turn units when the digit count required is above 2^{8}, depending on the code and antiambiguity logic in use. If 1,000 counts are required for full scale output, it may be accomplished by a disc with 10 counts and 10 revolutions, or by a disc with 1000 counts and one revolution. In the first case, a 10-

to-1 gear ratio would be required to turn the encoder disc 10 times for each revolution of the gear system input shaft. Gearing systems for encoders use spring-loaded Precision 3 gears (Table VIII) to minimize gearing errors. Total gearing errors must be less than the error of the basic encoder. Gear materials vary with the application; standard Precision 3 gears are made from 303 or 304 stainless steel or chromic acid anodized 24ST aluminum. For extreme corrosive atmospheres, the more difficult to machine 316 stainless steel may be used. Gear errors are illustrated on Figure 44. These errors can be checked with a gear test tape. Increased encoder resolution through physical gearing also changes mechanical input requirements. Input driving torque is greater by N times; inertia is multiplied by N^2 (N equals the gear ratio). Increased mechanical input requirements cause angular error and wear.

5.5.3 Weight of encoders.

5.5.3.1 Size and accuracy. Encoders can range in size from less than one inch to as large as 10 or 12 inches in diameter, and weight can similarly range from a few ounces to several pounds. Generally, encoder size must increase as requirements for transition accuracy become more demanding. It follows that as the overall size increases, the weight of the unit will increase proportionately. Weight is not normally a critical encoder characteristic, but in those cases (notably airborne applications) where weight is limited, the usual method is to select or design an encoder of smaller dimensions to achieve the required weight savings. Larger and more accurate encoders will involve inherent weight increases since the bulk of encoder weight results from the shaft, case, and bearings. As the disc size is increased, a larger, sturdier, and heavier shaft is required which, in turn, generates a requirement for larger heavier bearings and case. The challenge facing the encoder manufacturer is to attain high accuracy in a compact package with the attendant reduction in weight.

5.5.3.2 Density. The essential weight characteristic is not absolute weight, but rather the weight for a given size. Higher weight for an encoder of a given size can indicate higher component density and greater complexity. Complexity in encoder design usually will have an adverse effect on service life and reliability. However, a weight increase can also result from the use of heavier case and bearings or from special protection for unique operating conditions. In any case, it is important to determine the weight of an encoder unit and to determine if the weight is acceptable for the size specified. If the weight is uncommonly high (for example, eight ounces for a size 11 unit), the cause should be determined to ensure that the unit is not over-designed for the application and the design complexity should be carefully evaluated. If the weight is low, the structural integrity of the case and the weight and quality of the bearings should be evaluated to ensure proper performance levels. Table IX is a representative array of typical, state-of-the-art encoders comparing their size, performance, and weight.

5.5.4 Mountings and physical interfaces.

5.5.4.1 Background - mounting arrangements. In designing or selecting an encoder, considerable cost effectiveness can be achieved by specifying standard synchro sizes since this will simplify the mounting and other physical interface requirements. If encoders can be designed and constructed for standard synchro mounts, the numerous items of shelf hardware developed over the years for synchro attachment can be used. This eliminates the risk, expense, time, and effort of developing unique or special mounting arrangement. There will be, of course, certain specialized applications where standard mounts do not meet system requirements. In such cases special mounts may have to be developed. However, encoders and synchros are both units with essential rotating components and their similarity in size and configuration suggest a characteristic commonality that should be exploited to the fullest extent. Synchros have been in common use for a sufficiently long time to verify the effectiveness of the standardized items of mounting and coupling hardware, especially where a high degree of environmental resistance or efficient maintenance are critical to overall system performance.

5.5.4.2 Standard hardware. The items of standard mounting hardware described below were originally developed as synchro mounts and should be used whenever possible. Special tools designed for use with these mounts are also available. If non-standard mounts must be designed, the design principles demonstrated in the following examples should be used.

5.5.4.3 Moutning clamp assembly. The clamp assembly shown on Figure 45 consists of a captive screw, lockwasher, and clamp. Three clamp assemblies displaced from one another by 120° may be used to mount an encoder. If fewer clamp assemblies are used, an adapter assembly is required.

5.5.4.4 Clamping disc assembly. A clamping disc assembly consists of a clamping disc (see Figure 46), four captive screws, and four lockwashers. Standard clamping disc assemblies are available for encoders of standard sizes 11, 15, 16, 18 and 19. The four screws thread into four matching holes on the front or shaft end of the encoder. The pressure of the clamping disc against the interfacing panel or chassis holds the encoder in place.

5.5.4.5 Adapter assemblies. As shown on Figure 47, an adapter assembly consists of an adapter plus four captive screws and lockwashers. These assemblies are available for standard sizes 11, 15, 16, 18 and 19. The four screws fit into four tapped holes in the front end of the encoder. When an adapter assembly is used, the encoder is secured to the chassis or panel using mounting clamp assemblies.

5.5.5 Environmental determinants.

5.5.5.1 Environmental requirements. The ability of an encoder to continue to operate properly in spite of extremes in ambient environment and under arduous operating conditions is a design consideration with serious impact on both cost and performance. Requirements for environmental resistance are dictated by the system application and cover a huge range of possibilities. Encoders used in industrial control systems operate in a static, protected environment where space is virtually unlimited, where there are no significant weight restrictions, and such elements as temperature, moisture, and dust can be carefully controlled. Encoders designed for military combat or aerospace applications must be operable under the most austere field conditions where weight limits are critical, space is at a premium, and the barest minimum of protection from the elements is possible.

5.5.5.1.1 Cost vs. performance. Design or selection of an encoder with the required degree of environmental resistance is a tradeoff between cost and performance factors such as reliability, maintainability, accuracy and resolution. If cost is fixed, then performance level must be compromised for environmental resistance. If, however, performance is the prime consideration, then cost will increase as a direct function of environmental resistance. It is essential that each of these parameters be clearly defined early in the design process to achieve a truly cost-effective system. An encoder design that exceeds system requirements will incur costs out of proportion to the task, while a less expensive device may perform below required system levels. The final engineering decision between the many possibilities should be the result of successive iterations of the systems engineering process to ensure that the primary elements of cost, performance, and environmental resistance have been adequately satisfied.

5.5.5.1.2 Environmental resistance. As the range of possible encoder applications broadens, the range of environmental extremes and the need for special resistant qualities are similarly increased. The primary environmental considerations within current state of the art include such factors as shock, vibration, temperature, humidity, dust and foreign material, fungus and insects, salt atmosphere, barometric pressure, and solar radiation including thermal shock. General requirements for these elements are included in both military and industrial specifications (for example, MIL-E-4158 and MIL-E-16400) which are commonly invoked as an overall system design requirement. Numerous detail specifications are often used in conjunction with the more general documents. In any case, the required degree of environmental resistance must be clearly defined and identified to assure the necessary final system design.

5.5.5.2 Adaptability of design. The various encoder functions, the variety of encoder types and categories, the detection method, coding technique, and mechanical design all affect the performance of an encoder under extreme operating and environmental conditions. Of these factors, the most important is mechanical design. Many of the inherent disadvantages of one encoder approach or another which can result in sensitivity to environmental conditions can be overcome through improved mechanical design. Contacting encoders, for example, are the simplest and least expensive approach, but they can be seriously degraded by dust, sand, moisture, or other foreign matter. The simplicity of the contact approach can be retained by providing an encoder enclosure that affords total, sealed protection for the internal works. Similarly, contact encoders are more likely to be degraded by shock and vibration than optical or magnetic types. This fault can be lessened by a mechanical design that provides sturdiness and structural integrity, and by a mounting arrangement that absorbs the bulk of shock force or provides some measure of isolation. Compensation through improved mechanical design is not achieved without cost or risk, however. The penalties in cost, weight, and bulk of a special, environmentally resistant, mechanical design must be equated and compared with the increases that will result from an entirely different type of encoder to determine the best overall approach. An optical encoder may provide higher performance than is actually required for a given encoding task and still be the most cost/effective solution because the cost increase effected by the higher performance encoder may well be less than the cost of developing unique shock mounts or a moisture-tight sealed case for a lower performance device. Generally, contact encoders are the most sensitive to all environmental extremes; optical encoders are somewhat less sensitive, but many optical units do not perform well under extremes of shock, vibration, or temperature. Magnetic encoders have the greatest inherent resistance to all adverse ambient environments, but are sensitive to electromagnetic fields which may be created by adjacent equipment. Table X presents the results of a survey of currently available encoders and the levels of performance and environmental resistance that can be achieved.

5.5.6 Comparative evaluation of size and structure.

5.5.6.1 Summary of design. The mechanical design and arrangement of an encoder includes its size, shape, packaging, structure, weight, and mountings. Encoders are classed as rotating components; and although each specific type of encoder will have unique requirements, the general principles of good design for all rotating components apply to encoders. Encoder size sets the theoretical limits of encoder accuracy and resolution; as encoders become larger, they become proportionally heavier. Compactness and light weight are not often critical design considerations since most standard components fall well within present miniaturization needs. However, miniature encoders with uncommonly high requirements for accuracy and resolution require special development. Such special devices, in turn, result in high component density and complexity as evidenced by high weight per unit volume. This condition can result in lower reliability, shorter service, and more frequent maintenance. Structural integrity is gained through the use of heavier enclosures and bearings which not only influence accuracy, but are essential to provide resistance to shock and vibration. Additional resistance to shock and vibration can be gained from special mounting arrangements which absorb environmental phenomena or serve to isolate the encoder from them. It is best to use enclosures and mountings of standard sizes wherever possible since the use of shelf hardware that has been proven in service reduces both cost and risk. Mechanical arrangement is the design feature that is most frequently modified to meet environmental requirements. Of the multiple factors influencing the performance of an encoder under varying environmental extremes, mechanical design allows the greatest flexibility within the limits of a given set of design/performance parameters.

5.5.6.2 Conclusion - size and design. The size and configuration of an encoder are often dictated by system requirements - available space, weight limits, mounting provisions, or other immutable characteristics of the parent system. In such cases, the primary design problem is to pack the required encoder performance into the available envelope. However, where some latitude is allowed in the design or selection of mechanical arrangements, a more cost-effective system is possible. The key to an efficient design is the efficient careful tradeoff of encoder characteristics to arrive at the combination which provides the best blend of performance and economy.

5.6 Systems technology.

5.6.1 Input mechanics. The input function of an encoder in its simplest form is performed by a shaft which is coupled to the rotating variable and transmits the rotary motion to the encoder disc. As in any rotating part, there are three basic design considerations: speed, torque and inertia. Where these factors are of a form and value that can be utilized by the encoder system directly, no further input processing is required beyond a simple shaft and coupler arrangement; assuming adequate bearings are used and provisions are made for attachment of the encoder disc. In many encoder systems the motion of the variable input is either too fast or too slow for convenient processing. In such cases, the input can be modified to increase encoder accuracy, to improve reliability, to lengthen service life, or to simplify the overall encoding task.

5.6.1.1 Torque as design consideration. Torque is simply a measure of how much load can be turned. In power-producing machines (motors, engines, and so on), torque is used to express the amount of rotational force which the unit can generate; and the force is often sufficiently large to be measured in pound-feet. Encoders do not produce torque, but rather require a certain amount of input force to move their works. The breakaway and running torque figures for an encoder are functions of the load which the input variable must turn, usually expressed in ounce-inches or gram-centimeters. Therefore, the weight and size of the components used in the input section of an encoder can be critical. The design of an encoder must ensure that both the breakaway torque and the running torque are kept to a minimum, since excessive loading of the input variable can introduce a significant instrument error. The moving parts of an encoder must be as small, as light, and as friction-free as possible. Use of low friction bearings and careful alignment during manufacture to ensure perpendicularity are the most essential factors in systems employing a directly coupled input. However, in systems which use an input gearing arrangement, the reflected torque of the gear train must also be considered. Gears should be designed and selected for low torque, and the gear arrangements must be carefully analyzed to determine the reflected torque. Table XI lists the running torque and breakaway torque requirements for a representative array of currently available encoders.

5.6.1.2 Inertia as design consideration. In many encoder applications, the input variable does not revolve in the same direction nor at a constant speed. The input variable may speed up, slow down, stop, start, and change direction many times in the space of a few seconds. The sensitivity and reaction of an encoder result from the ability of the encoder to sense these changes and to produce an appropriate changing output; inertia is the prime input factor affecting the ability of an encoder to respond to changes in rotational speed. The inertia of a number of state-of-the-art encoders is listed in Table XI.

5.6.1.2.1 Input speed. As the inertia of an encoder increases, the sensitivity decreases and the ability to respond to change is lessened. This is not necessarily a negative performance factor. In high, constant-speed encoders, where reaction to input acceleration or deceleration is neither required nor desired, the inertia factor inherent in the input section provides an important stability factor. It ensures that disc rotational speed remains tolerably constant even though some unwanted variations in the input speed may occur.

5.6.1.2.2 Most important design features on inertia. The encoder design features with the greatest influence on inertia are the size and material density of the rotating parts and the efficiency of the bearings. In designing or selecting an encoder with a system requirement for quick reaction to speed changes and to fast, frequent starts and stops, low inertia is essential. This can be achieved by using high-precision bearings and by keeping the diameter of the disc as small as possible, consistent with other performance requirements such as accuracy or resolutions. If the disc size cannot be reduced, the density factor can be manipulated through the use of high strength, lightweight materials. If input gearing is used for speed conditioning, this will increase inertia. The quality and precision of the gear train must be carefully considered and its inertia evaluated. Again, the size of the gear parts and the density of the materials used to fabricate them are important factors influencing inertia. However, the single, most important design option to ensure the least inertia is the use of high quality precision bearings (ABEC 7 or better).

5.6.1.3 Speed as design consideration. The speed at which the input variable rotates is a factor in encoder design that not only affects the mechanical design requirements, but has an equally important effect upon detection, logic processing, and output. In addition, the speed factor can be a limiting parameter for accuracy, resolution, reliability, service life, and other systems considerations. The speed of rotation, for example, will determine the number of revolutions that the rotating parts of the encoder must make for a given unit of time. This, in turn, will determine service life which is usually expressed as a function of cycles or revolutions. An encoder with a rated service life of 1,000,000 operating cycles will be expected to have a shorter absolute service life as rotational speed increases.

5.6.1.4 Performance Parameters of design and construction. It is an often repeated maxim that the disc is the heart of an encoder. The design and manufacture of the disc does, indeed, set the theoretical performance limits for encoder accuracy and resolution. However, the details of the mechanical design and construction of the encoder input functions have at least equal impact on encoder performance in terms of practical operating hardware. Regardless of the sophistication and precision of the encoder disc, the actual overall operating performance of the encoder is ultimately limited by the quality of the input components.

5.6.1.4.1 Bearing quality. The first and foremost limit on encoder performance is bearing quality. At present, encoder discs can be designed and manufactured to accuracies and tolerances far in excess of the performance levels which can be realized from state-of-the-art bearings. To derive the complete design accuracy of a given encoder disc, a bearing complex would have to provide an errorless mounting and rotational arrangement, a goal which cannot be achieved. Bearing runout, preload, inertia, and friction all introduce some measure of error and even the highest grade of presently available bearings fail to operate at accuracy levels commensurate with those attainable in disc design and manufacture. Thus, any dramatic improvement in the operating performance of encoders must depend upon breakthroughs in either bearing design or the development of new and improved input techniques.

5.6.1.4.2 Major design factors. Design and construction of such input components as bearings, shafts, gears, and couplings affect operating levels in two ways. First, the size and general arrangement determines the theoretical operating level; second, the details of the manufacturing process determine the amount of the design capability that is realized in the actual hardware translation. The major factors to be considered are size of parts, bearing preload and runout, shaft windup, and shaft perpendicularity and concentricity. Encoders can resolve an input shaft position to greater than 2^{18} (one part in 1,296,000). Generally, the single recurring critical factor in the design of an encoder input function is the bearing. Table XII presents a criteria for the bearing quality required for the three general categories of encoders in present wide spread use.

5.6.1.4.2.1 Component size. Instrument error has considerably lessened impact on overall encoder performance as the size of input components increases, especially the diameter of the encoder disc. Bearing radial runout of 5×10^{-6} measured at one inch from the center of the disc (axis of rotation) will induce an error factor of ±0.5' arc); at 10 inches the error is reduced to ±0.01' arc. Thus, the requirement for compact, miniature packaging generates an additional requirement for increased precision in the design or selection of bearings.

5.6.1.4.2.2 Shaft characteristics. Bearing performance and bearing characteristics determine the perpendicularity and concentricity of the operating encoder. The shaft mounting and bearing arrangement must provide for parallelism as a minimum mandatory requirement and absolute concentricity as a theoretical design goal. Shaft windup depends on the quality of the shaft material and such encoder design characteristics as bearing preload, input torque, inertia, and load. The bearing preload will determine, to a large extent, the amount of load which can be borne by the shaft. Nevertheless, the sum of the various critical input characteristics must not exceed the rated shaft load.

5.6.1.4.2.3 Use of a gear train. A gear train is a component commonly used in the input section of an encoder to control or modify rotational speed. It is equally common to use a gear train between the high-speed and low-speed section of a multi-turn encoder. This technique does not change the basic resolution of the encoder, but it does change the total count capacity. In the typical multi-turn encoder scheme shown on Figure 48, the resolution is 8 bits but the total count is 13 bits. Thus, if the input variable rotates 32 turns, a 13-bit output would be produced. The gear train ratio is a function of the number of bits on the low-speed disc. With a 2^n gear train, up to n bits can be placed on the low-speed disc. In practice, the low-speed disc will contain fewer bits than the high-speed disc and the gear ratio is limited to 64:1 (2^6:1). Unless some form of compensation is used in the scanning logic, the gear train can contribute to overall encoder error. Most units employing this technique are designed with a scanning technique that eliminates this disadvantage by inhibiting readout of transitions on the low-speed disc when the encoder is counting. This ensures that backlash and gearing error are not seen at the encoder output .

5.6.1.5 Interface and integration. The consideration of interface and integration of encoders with a parent system involves two basic requirements: mounting and coupling. The mechanics and techniques of encoder mounting are discussed in 5.5; however, the design and arrangement of the mounting which affect the performance requirements of the input function are discussed further in this section. In designing an encoder/system interface, the main objective is to provide an accurate, efficient transfer of the rotation of the input variable to the encoder with the absolute minimum loss or distortion of intelligence. The main design problems arise from considerations of alignment, torsional error, shaft windup, and slippage. These factors determine such specific solutions as placement, relative arrangement, and coupler design or selection.

5.6.1.5.1 Mounting requirements. Mounting requirements are more stringent for high-resolution devices, and this problem can be further intensified in miniaturized equipment. Ideally, the encoder should be mounted in perfect alignment with the rotating input variable so that in operation, the integrated system is rigid on the rotational axis. Achieving this theoretical standard can be difficult and expensive. The primary method for attaining the required input accuracy without the subsequent need for overly precise mounting tolerances is to increase the displacement between the input variable and the encoder shaft and use a relatively long coupling device. Under these circumstances, the effect of shaft misalignment is minimized. Slippage, torsional error, binding, and windup are still problems which must be carefully considered and solved.

5.6.1.5.2 Couplings. Couplers are available in three basic types: metal bellows, precision laminated, and a simple sleeve with a keyway. In selecting a coupler, the primary consideration is the load or stress that must be borne (thrust factor, axial loading, radial loading, and so on). The coupler must provide for the transfer of energy with minimum angular windup. The exact type of coupling needed to achieve the desired encoder performance depends on the details of system design and configuration. Where possible, standard coupling devices with known performance characteristics should be used to minimize development and acquisition cost, and engineering risk. This is not always possible, and coupling configuration is often a significant tradeoff factor in developing an optimum, integrated encoder system. Figure 49 depicts an array of coupling devices currently available as standard, shelf hardware items. Sometimes it will be necessary to either design a unique coupler, especially for a new precision application, or to modify an existing design to meet a specific need. The basic performance criteria and design requirements outlined in this section must be considered carefully.

5.6.1.6 Comparative analysis of hardware. The input function of an encoder is the operating mechanical interface between the rotating input variable and the digitizing operation performed within the encoder. The spectrum of design possibilities for performing this function is sufficiently broad to provide numerous choices in the selection of a specific means of instrumentation. In this section the design considerations are synthesized in summary form to frame some basic rules for design tradeoffs. Each of the options in the input function has inherent advantages which the system designer may need to employ. For each advantage there is a resulting penalty that must be evaluated and compared to yield a system with the particular mix of input characteristics required for a given encoding task.

5.6.1.6.1 Rotating components. The input hardware must couple the mechanical energy accurately and reliably with minimum loss, distortion, and loading. The performance of the input function has a primary, limiting effect on overall encoder capability even though a number of logic processing circuits and other forms of electronic compensation are often used to overcome a certain degree of this limitation. Basically, the encoder can only detect and digitize the motion transmitted to its internal works; it follows that the quality of the detection is limited by the accuracy and precision with which that energy is transferred. Considerations of speed, torque, and inertia are primary in the design of the rotating portions of the input function. In addition, the input shaft must be mounted to ensure parallel alignment as a mandatory minimum and absolute concentricity as a theoretical design goal. Low inertia is a primary requirement for sensitivity; that is, quick reaction to rapid starts, stops, and changes in direction. However, inertia can also be used as a stabilizing factor. Speed, torque, and inertia all contribute to shaft windup which should be kept to a minimum.

5.6.1.6.2 Bearings. In actual hardware design and selection of components, the first limitation on encoder performance, especially in terms of cost, is bearing performance. Bearing preload affects the amount of bearable shaft load; bearing runout determines shaft perpendicularity, parallelism, and concentricity; and bearing friction affects inertia, torque, and shaft windup. All these factors combine to set the theoretical design limits of encoder performance. Bearing performance, in turn, interacts with component size since the requirement for bearing precision increases as the diameter of the rotating components decreases. Thus, the allowable size of the parts (shaft, disc, gearing) and the quality of the bearings (runout, preload) will determine the operating limits for encoder precision.

5.6.1.6.3 Coupler. The other main component of the input function is the coupler, the hardware which connects the input variable to the encoder shaft. The coupler can provide a means for overcoming minor mounting misalignment, but generally the coupler, like the bearing, limits rather than enhances encoder performance. An optimum coupler design minimizes torsional error, slippage, and angular windup. Ideally, the coupler must provide an input arrangement that is rigid on its rotational axis.

5.6.1.6.4 Gear train. Input gearing is a common method of increasing encoder resolution. However, the gear train, like other mechanical components, limits encoder performance by introducing inertia, loading, and other factors which can degrade input accuracy.

5.6.2 Detection mechanics.

5.6.2.1 Ambiguity in scanning. A shaft position encoder cannot be constructed so mechanically perfect that two or more sensors can be consistently depended upon to operate simultaneously in perfect synchronization. There will always be some small angle at which there will be a momentary misalignment or unsynchronized condition. At this point an erroneous or ambiguous output will be produced (refer to 5.3). In the 8421 natural binary shown on Figure 50, several sensors must change simultaneously; for example, when the decimal count changes from 7 to 8. If the binary 2 bit (21), for example, should fail to change condition at the same time as the other bits, there would be a brief period of perhaps a few milliseconds when the 8, 4 and 1 bits would be properly conditioned for an 8 count and the 2 bit would still be conditioned for a 7 count. During this brief span, the encoder output would be an erroneous 10 count; and interrogation is as likely to occur at this point as any other.

5.6.2.2 Non-ambiguous coding. A number of coding techniques are discussed in 5.3 which solve this ambiguity problem by mechanical or electrical detenting. A window code technique as shown on Figure 51 is a common form of electrical detenting. The outer track is the “window” and readout is permitted only when sensors are energized by this track. If continuous data is required, the encoder is instrumented with an output storage circuit that follows when the window is on and stores when the window is off.

5.6.2.3 Gray code. Codes which require only one bit to change when either increasing or decreasing by a count of one are by nature non-ambiguous. Since only one bit changes, it is impossible to generate erroneous data. This technique is called unit distance coding. The Gray code scheme shown on Figure 52 is an example of a unit distance code which can be easily converted to the familiar natural binary notation system by employing a parallel Gray code to binary translator with exclusive OR circuits. Gray code can be translated in serial, most significant digit first in one word time, or least significant digit first in two word times. Computation usually proceeds least significant digit first, while data recording and transmission usually proceeds most significant digit first.

5.6.2.4 Cyclic code. Cyclic decimal code is a monostrophic code similar to Gray code in that it ensures non-ambiguous outputs. As shown on Figure 53, cyclic decimal coding is also easily converted to natural binary form. Cyclic decimal code can be translated in serial by character, most significant digit first, for data transmission or recording. It is often convenient to store the cycle decimal code in parallel and perform odd-even sensing and complementing (exclusive OR operation) on the D bit in the storage register. The modified code can then be transmitted and/or translated to decimal, serially by character, most significant digit first or least significant digit first.

5.6.2.5 Scanning. Scanning is the scheme or pattern for arranging sensors in the detection function to derive the encoder output. The sensors can be contacts, magnetic pickups, capacitive elements or photocells depending on the particular type of encoder. In any case, the arrangement of sensing devices determines to a large degree the overall capability of the encoder, especially the ability to produce concise, non-ambiguous outputs. Ambiguity can be eliminated by the use of unique codes, but these codes required the addition of some special form of decoding network. These additional circuits can increase the size and the cost of an encoder, often beyond the limits of primary system requirements. A number of scanning methods have been developed to correct this deficiency. The scanning methods discussed in this chapter include:

a. Line scan.

b. V-scan.

c. M-scan.

d. U-scan.

e. Self-selecting scan.

f. Special scans.

5.6.2.6 Line scan. Originally, scanning was a simple matter of positioning sensors in a vertical row across the disc pattern. When more bits were added to the disc and encoders became smaller, the incremental bit size decreased to a point where the placement of the sensor became more critical. If a sensor transitioned into the next bit before the other sensors, an ambiguous reading was obtained and, because of the pie-shaped configuration of the bits on a disc, the critical bits occurred on the more significant bit. This early rudimentary scanning method is called Line scan since a simple vertical line of sensors is used. The typical implentation of this technique is shown on Figure 54. Line scan does not solve the ambiguity problem; it is the simplest, most direct method and is usually employed when special non-ambiguous codes are used with decoding networks. Line scan is a basic technique and does not provide any special capability other than a standard reference point for the detected encoder count.

5.6.2.7 V-scan. One of the first scans developed to produce non-ambiguous outputs was V-scan. In the basic V-scan configuration shown on Figure 55, the sensors are positioned across the pattern in the form of an inverted V. The apex of the V is placed on the least significant track of the disc pattern and two sensors are placed on each succeeding track. The two sensors are spaced at an interval equal to the size of the bit preceding it. Interrogation is sequential since each sensor controls the sequence of subsequent interrogations. The sensor immediately clockwise from the sensor being counted is called the leading sensor, and the sensor in the counter-clockwise position is called the lagging sensor. The typical V-scan interrogation network shown on Figure 55 reads the next leading sensor if the LSD bit is On, and reads the next lagging sensor if the LSD bit is Off. This process is repeated until the total bit count of the encoder has been read. Stated another way, V-scan solves the ambiguity problem by using two sensors for each bit; and the external switching logic selects the proper output. Since the sensor selected for readout is at all times a minimum of half the bit width of the least significant track from the transition point, the sensor selected to readout the nth track is the lagging sensor when the (n-1)th bit is On. Conversely, the leading sensor is selected to readout the nth track if the (n-1)th bit is Off. This can be stated in Boolean notation as:

$$2^1 = 2^0 \cdot 2^1{}_{lag} + \overline{2^0} \cdot 2^1{}_{lead}$$

V-scan translation may be performed either in parallel or serially. If serial readout is used, it must proceed LSD first. A manufacturing variation of V-scan is sometimes used which provides a separate track for the lead and lag sensors as shown on Figure 56. This approach doubles the number of tracks required on the disc; but for contacting encoders, especially of the brush type, several advantages accrue which more than offset the penalty of disc complexity. First, separate tracks for each brush result in reduced wear and improved lubrication. Second, the tracks rather than brushes can be staggered resulting in all brushes lying in a single radial line. This change provides more accurate alignment of the brushes and greater structural strength for improved shock and vibration performance. The resolution of a V-scan encoder can be doubled without a similar increase in manufacturing accuracy by adding one track to the disc and a sensor to read it. This method combines V-scan with unit distance code; unit distance code is used for the first two bits and V-scan for the remainder. V-scan is an efficient technique for providing non-ambiguous outputs; but the method has the disadvantage of requiring two sensors, two

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diodes and, optionally, two tracks for each bit and considerable external switching logic.

5.6.2.8 M-scan. M-scan is a variation of V-scan. The major difference lies in the fact that in M-scan the lag tracks or sensors are in complemented form relative to their lead track counterparts. M-scan was developed for special computer applications. Figure 57 shows a typical M-scan pattern using separate lead and lag tracks which enable the sensors to be arranged in a single radial line. The Boolean notation for M-scan is effectively the same as the V-scan except that different functions are available from the encoder. Similarly, the advantages and disadvantages enumerated for V-scan apply equally to M-scan with appropriate allowances for the specialized nature of the M-scan technique.

5.6.2.9 U-scan. Following the development of V-scan and its variation, M-scan, U-scan was developed to overcome some of the limitations found in the earlier approach. U-scan has the advantage of providing required outputs for almost any code or number system since the successive positions on the disc can be any arbitrary sequence of unrelated binary numbers. A typical U-scan scheme is shown on Figure 58. In U-scan the two lines of sensors are positioned across the disc pattern in an inverted U configuration. The sensor at the apex of the U is placed on the LSD track, and the succeeding sensors are placed by pairs on the other tracks. The displacement of the paired sensors is equal to the size of one bit on the track of interest. Only one step of interrogation is made with lag sensors reading out when the LSD bit is On and lead sensors reading out when the LSD bit is Off. As in V-scan and M-scan, an external switching network is required for sensor selection. U-scan logic is similar to V-scan; the difference is that the LSD bit is used not only to select the next bit, but to select the next group or belt of bits. This can be expressed in Boolean notation as follows:

$$2^1 = 2^0 \cdot 2^1_{lag} = \overline{2^0} \cdot 2^1_{lead}$$

$$2^2 = 2^0 \cdot 2^2_{lag} = \overline{2^0} \cdot 2^2_{lead}$$

$$2^3 = 2^0 \cdot 2^3_{lag} = \overline{2^0} \cdot 2^3_{lead}, \text{ and so on.}$$

A major advantage of not requiring the generation of the complement of every bit is that all of the lead tracks (2^1_{lead}, 2^2_{lead}, and so on) can be commonly connected and controlled by the function $\overline{2^0}$. Similarly, all of the lag tracks can be connected together and energized as a function of the 2^0 bit. The manufacturing tolerance for the disc pattern with the sensor placement is ± one-half the value of the 2° selector bit. This tolerance is an angular, rather than a linear, value so that meeting the tolerance requirement becomes more difficult and more costly for each track on a disc as the radius decreases. To increase these tolerances it is common to divide the disc into two belts. The complement of the most significant bit on the outer belt is generaed. This bit and its complement are the driving functions for the inner belt. By using two bits on the first belt, the manufacturing tolerance on the second belt is increased four times. If three bits are used, the tolerance is increased eight times. This principle is shown on Figure 59. The outside track or tracks are usually denoted as the selector track(s). The outer belt is called the alpha (a) belt, while the inner belt is defined as the beta (ß) belt. One disadvantage of this belting arrangement is that the output from the beta belt is reduced by the sum of two diode voltage drops in series. This is usually not a problem unless very low potential circuits (less than 6V) are used. It is possible to modify the U-scan technique to eliminate diodes altogether. This is sometimes important in applications involving high nuclear radiation. The modification consists of producing a pattern in which the leading edge of all tracks are connected to 2^0, and the trailing edge of all tracks are connected to $\overline{2^0}$. The center portion of each track is connected to a constant source of potential. The resolution of this pattern is only one-half to one-third as good as the simpler U-scan technique; for this reason, it is less frequently used. Resolution can be doubled with the same manufacturing tolerance by adding one more track and brush to generate the function G. This function is identical as described under V-scan techniques. The illustrations of U-scan have been shown with familiar binary and BCD codes for simplicity. However, the techniques described can be applied to any code. Usually, the selector bit is the least significant bit of the required code. This, however, is not necessary. The selector bit may act simply to switch the output from the lead and lag tracks without being any part of the output code. Under these conditions the resolution for a given diameter disc and manufacturing tolerance is reduced by one-half.

5.6.2.10 Self-selecting scans. All of the important scanning techniques have the disadvantage of requiring a significant amount of external circuitry to select the proper sensor for readout. A number of self-selecting variations have been developed to overcome this difficulty and reduce the size and expense of external selection circuits. In this section a self-selecting technique is described for both the basic V-scan and U-scan.

5.6.2.10.1 Self-selecting V-scan. The external switching circuits normally required for sensor selection in a V-scan encoder can be reduced by using additional tracks, sensors, and diodes. The logic equations for the self-selecting variation are essentially the same as for basic V-scan:

$$2^1 = 2^0 \cdot 2^1{}_{lag} + \overline{2^0} \cdot 2^1{}_{lead}$$

$$2^N = 2^{N-1} \cdot 2^N{}_{lag} + \overline{2^{N-1}} \cdot 2^N{}_{lead}$$

The function $\overline{2^0}$ is formed by a separate, active circuit (such as a transistor or relay) which is used to invert 2^0. The AND functions are derived by sensors and coded circuit patterns connected in series. The coded circuit patterns generate $\underline{2^1}_{\text{lead}}$ $\underline{\text{and}}$ 2^1_{lag}. Additional sensors and tracks are used to generate 2^1_{lead} and 2^1_{lag}, while the OR functions are obtained using diodes. Thus

$$2^1 = 2^0 \cdot 2^1_{\text{lag}} + \overline{2^0} \cdot 2^1_{\text{lead}}$$

$$\overline{2^1} = 2^0 \cdot \overline{2^1_{\text{lag}}} + \overline{2^0} \cdot \overline{2^1_{\text{lead}}}$$

The generated functions 2^1 and $\overline{2^1}$ are used as common inputs to the next set of sensors, tracks, and diodes as shown on Figure 60. By advancing and retarding the sensors rather than the tracks, a single track is used to generate both 2^1_{lead} and 2^1_{lag}, while a second single track generates 2^1_{lead} and 2^1_{lag}. For this reason, most self-selecting V-scan encoders are manufactured with a staggered arrangement of sensors similar to that shown on Figure 61. Self-selecting V-scan has the advantage of generating both true and complement, but has the disadvantage of requiring three tracks, four sensors, and two diodes per bit. The really serious shortcoming of the self-selecting version of the V-scan technique occurs when low voltage transistor circuits are used which require a chain of diode circuits with up to 1 volt per bit drop in signal level below the reference or supply potential. Also, in contact encoder applications, the brush or pin sensors are in series, and the contact noise can be transmitted to the higher order outputs. In arriving at a design decision, these disadvantages must be carefully weighed and compared to the advantages of reduced external logic and availability of bit and complement outputs.

5.6.2.10.2 Self-selecting U-scan. In the self-selecting version of the U-scan, two separate disc patterns are used rather than the two lines of sensors; and a separate clock or timing track is used to control pattern switching (see Figure 62). The clock track acts as a trigger which alternately energizes the commons of either the lead or lag track. This switching is accomplished through a flip-flop which isolates the information tracks from the clock track sensors. The flip-flop also enables the information sensors to carry higher currents, because in other types of scans the entire load must be carried by the switching sensor, usually the LSD, which also is switched for every step of progression. The pattern on Figure 41 shows that any two given bits are offset from each other by one-half bit, which means that there is a one-half bit overlap. This overlap introduces a delay of one-quarter bit before that bit is switched on. This quarter bit delay provides the non-ambiguous aspect of the scan. Since the only electronics required for this scan is one flip-flop per disc, and the isolation diodes, all the electronics can readily be packaged within the encoder envelope making this design one of the few self-contained, self-selecting encoders. Self-selecting U-scan is effective with any code, and is especially useful where accuracy of switching is primary, such as in the second and third discs of a multi-disc Gray code encoder.

5.6.2.11 Special scans. Scanning techniques can have almost infinite variety, and each manufacturer incorporates some unique feature of variation in a constant attempt to make his product better. New individual encoder designs are being developed every day in response to specialized needs that include improvements and variations in scanning and interrogation. Thus, most encoders use some form of special scan. One manufacturer, for example, has developed a scanning method which uses a clock track with one fourth the resolution of the LSD bit and two encoding patterns which are complements of each other. The outputs of the encoder are supplied by set-reset flip-flops which remain in the state to which they are pulsed. If the output flip-flop is turned on, it remains on until a pulse is developed to reverse the condition. In operation, the binary pattern sets the flip-flop and the complement pattern provides the reset signal. Since the clock bit is one fourth the resolution of the LSD bit, the sensor must commutate well into the bit before the pattern pulse is generated. The flip-flops isolate the output of the encoder from any noise that may be generated internally. This approach provides a device of extremely noise-free operation with the capability to switch signals of fairly high current level and a substantially extended expected service life. This is only one of many such examples which could be given. The foregoing is basically a U-scan encoder with some special variations. Most encoders fall into this category, and although each device is unique in one or more ways, each device is also a design variation of one of the basic scan methods. The details of most special scans are either proprietary in nature or so specialized as to have limited use other than the one for which they were developed. Special scans can be developed to meet almost any esoteric need or application.

5.6.2.12 Preventing ambiguity in multi-turn encoders. Particular care must be exercised in selecting a scanning method for multi-turn encoders to ensure a non-ambiguous output. In multi-turn encoders, the friction or backlash in the gearing must be added to the other manufacturing tolerances that prevent simultaneous switching of several bits. V-scan and U-scan techniques provide sufficient tolerance to accommodate this added source of misalignment. With U-scan, each additional disc requires one or two more additional belts. Each additional belt adds one more diode in series with the lower order outputs. In some applications it becomes necessary to add inner belt amplifiers to restore the signal level. The design of these inverters must ensure they are capable of driving all bit lines in parallel.

5.6.2.12.1 Window code. If a window code is used on the high-speed disc to eliminate ambiguity, two additional selector tracks should be added to the high-speed disc which are connected in series with the lead and lag commons on the low-speed disc. In other words, with window code on the high-speed disc, U-scan should be used on the low-speed disc.

5.6.2.12.2 Unit distance codes. When unit distance codes are used on the high-speed disc, several alternate choices are available. If intermittent motion gearing (such as geneva gearing) is used, the low-speed disc advances one count for each half revolution of the high-speed disc and advances only when the high-speed disc is at zero, plus or minus a fraction of a count. At zero, no bit on the high-speed disc changes so the unit distance (monostrophic) property of the entire coded output is maintained. Alternately, simple spur gearing can be used with U-scan technique on both the low-speed and all successive discs. The drive circuits for the lead and lag commons are usually obtained from a special selector track on the high-speed disc. There is a third method useful with unit distance codes that employs a redundant or overlapping bit on the low-speed encoder. The discs are phased such that the output from the low-speed disc lags the output of the high-speed disc by 90° as measured at the high-speed disc. By comparing the overlapping bits, it is possible to determine when the high-speed code has changed but the low-speed disc has not. In such cases the output of the low-speed disc is increased by one. This technique is useful when the data is used in a computer or other circuits which provide addition at no cost penalty. Figure 63 shows a typical example of multi-turn encoder logic using overlapping bit techniques. The rules for translating the output of a multi-turn encoder to natural binary form can be summarized as follows:

(1) Store data.

(2) Translate low-speed value to binary.

(3) If the 2^0 bit (binary notation) of the low-speed section equals logical “1” and nth Gray code bit of the high-speed section equals logical “0”, add 1 to the value stored.

5.6.2.13 Scans - summary. Ambiguity is an inherent problem with digital encoders resulting from the mechanical limitations of encoder hardware and the structure of natural binary number systems. Monostrophic or unit distance code systems, such as Gray code window coding, are commonly used to overcome the ambiguity problem; however, this approach requires the use of external decoding circuits.

5.6.2.13.1 Scan comparison. The scan of an encoder is the pattern or arrangement of sensors and light sources relative to the encoder disc pattern. Originally, sensors were simply placed in a vertical line across the code pattern. This technique, known as Line scan, provided readout but did not solve the ambiguity problem. As encoders became more sophisticated and requirements became more demanding, scanning schemes were developed to increase encoder performance. The two major types of scan are V-scan and U-scan. The name of the scan is descriptive of the pattern of sensor placement. Additional variations were developed including M-scan, a special form of V-scan, and several self-selecting forms of both V-scan and U-scan. V-scan and its numerous variations provided a large improvement over previous readout techniques, but, it also carried certain disadvantages. V-scanning requires considerable hardware to implement and requires complex external switching logic. The M-scan variation on basic V-scan was developed to provide both binary unit and its complement for special computer application. M-scan provides these additional capabilities, but retains all of the basic faults of V-scan. U-scan is a higher performance approach which can provide non-ambiguous outputs for any coding arrangement, including any numeric progression. The technique provides a dramatic increase in capability, but carries a proportional penalty in cost and complexity. Both V-scan and U-scan, in their many forms, require external switch logic to control sensor selection. Self-selecting scans have been developed to lessen this requirement. Although self-selection provides better performance, the technique adds to manufacturing cost and the resulting encoder is a device of much greater complication. Additionally, there are a number of detailed circuit disadvantages that need to be carefully evaluated for their impact on specific applications to ensure that the disadvantages do not outweigh the gains in using a self-selecting scan technique.

5.6.2.13.2 Performance vs. cost. Performance must be equated against acquisition price and cost of ownership (life cycle costs) to determine the cost/effectiveness of a candidate encoder scanning method. Usually, the more complex and expensive scanning approach provides greater performance (speed, resolution, compactness, accuracy, and so on), but does not necessarily add to unit reliability or maintainability. Selection of a higher cost device with performance capabilities in excess of system design requirements is not generally feasible since the increase in performance can rarely be realized in better longevity or reliability at reduced performance levels. In summary, the lowest cost, lowest performance device that can be developed commensurate with system performance and design requirements is usually the best system solution.

5.6.3 Logic mechanics.

5.6.3.1 Logic circuits - purpose. Logic circuits and networks form an important part of most digital encoders in current use. As applications become more ambitious and increases in encoder performance reliability become necessary, requirements for logic components and systems will become proportionately more demanding. This section presents a description of the basic types of circuits used in encoder systems, and an explanation of how these circuits can be used to solve systems problems. It also explains how to provide encoder outputs in a form adapted to the demands of current military and industrial equipment. Military approved logic diagram symbols most used in encoder literature are shown in Figure 64. Additional symbols may be found in IEEE-91 if required.

5.6.3.2 Logic circuits - function. Logic circuits and networks provide an electronic means of timing and controlling the format of an encoder output signal. Primarily, logic circuits are used in selecting sensors to implement a particular scanning or coding method, to store or count output pulses, to convert an output signal to the form required by the parent system, or to perform a number of these functions in combination. Additionally, logic circuits are used to perform such specific functions as latching, sampling, or parity validation. the general nature of the logic processing function is discussed in 5.3.3, and the relationship of logic processing to encoder performance and reliability is discussed in 5.7 and 5.10.

5.6.3.3 Latch circuits. Latch circuits are used to minimize the effect of noise on the dependability of contact encoders. Tests have shown that a conducting sensor is likely to produce erroneous outputs as a result of noise, since noise can make a conducting sensor (closed contact, for example) appear to be non-conducting for short intermittent periods. The likelihood of noise causing an interruption of output is at least 1,000 times greater than the probability that noise will produce an extraneous output . The problem is that noise is very likely to interrupt the output of a conducting sensor, but will almost never cause an output when a sensor is not conducting. A typical latch circuit is shown on Figure 65. During the sample interval, if a True signal (conducting sensor) appears at the input for the minimum detection period, a True signal will be stored by the circuit. To store new data, the control signal must first go False to clear the previous signal and then return to True. The encoder sampling gate is turned On. If the encoder sensor conducts (closed contact) while the gate is On, a True signal will be produced as an output. This True output signal will feed back through the AND gate, maintaining the True output signal even though noise may interrupt actual encoder signal and cause the sensor to appear to be non-conducting (open contact). The response time of the latch circuit shown on Figure 65 should be limited to approximately one-fourth the sampling rate by the proper design of the filter. If the circuit is designed for a faster response time, incorrect responses could result from noise signals and extraneous true signals could be detected. Latch circuits are not effective in excessively noisy encoders, and a system in which noise has not been reduced to negligible proportions can never be accurate or reliable. The use of latch circuits can improve the performance of a relatively noise-free encoder by reducing the error rate as much as 1,000 times and extending useful life by as much as 10 times. However, latch circuits cannot be used to overcome a basically faulty encoder design which is subject to excessive noise. In such cases, addition of a latch circuit may actually intensify the problem. The first consideration must be improvement of the basic encoder design.

5.6.3.4 Sampling circuits - design problem. Selecting or designing sampling circuits for an encoder is a function of the coding, the scan technique, and the manner in which the parent system must receive data. Proper selection of a sampling network can do much to reduce the wear factor and improve reliability by ensuring that power is applied to sensors only during interrogation. Some of the essential design considerations are:

a. Coding.

b. Scan technique.

c. Encoder speed.

d. Length and capacitance of lead cables.

e. Operating environment.

f. Type of readout: continuous, pulsed, serial, parallel.

g. Error rate.

The following discussion presents some typical approaches for both monostrophic and polystrophic encoders.

5.6.3.5 Monostrophic codes. Gray code and cyclic binary code are typical monostrophic or unit distance encoders. These encoders require the simplest logic control exclusive of the translation or decoding circuits. Figure 66 is a functional diagram for a typical 13-bit, multi-turn, geared Gray code encoder with a resolution of 10 bits (1,024 positions) per revolution of the high-speed disc. This includes nine bits of data repeated twice per revolution and one bit for selection of lead or lag sensors for the low-speed disc. This unit distance code encoder can be designed so that no selector is required between stages. Due to other considerations, some encoders of this type require the double inverter as shown on Figure 44.

5.6.3.5.1 Used with long cables. When long cables are used and if the drive circuit is remote, particular attention must be given to the time necessary to change the cable capacity. When the S bit changes state, the cable capacity must be charged or discharged through the load resistance. Following this, the drive circuits must charge or discharge the capacitance of the cable to the common sensor and from the bit on the low-speed disc that is changing. Because a monostrophic code is used, only one bit is changing and only the capacity of single line needs to be considered. The sum of these delays must be less than one-fourth the minimum quantum time. If this is not possible, then all bits from the high-speed disc, including the S bit, must be stored. After a delay sufficient to charge cable capacity, the output of the low-speed disc may be stored.

5.6.3.5.2 Direct coupling. Sampling circuits and drive circuits are not required in encoders using monostrophic coding, which is a distinct advantage. The output is always current and useful and can, for example, be directly coupled to a comparison circuit for continuous feedback in a servo control system. With monostrophic codes, a maximum of one bit is changing at any one instant. If the bit is changing, there is some uncertainty whether the bit is recognized as True or False. In either event, one of two adjacent numbers is recognized. Since the actual encoder position, when a bit is changing, is halfway between the two adjacent numbers, either readout is equally correct.

5.6.3.5.3 Storing. If a monostrophic code is to be stored, the variation in time delay in the response of the storage circuits or the duration of the sampling gate must be less than the minimum quantum time if no error can be tolerated.

The minimum quantum time (T_C) is: $T_C = \frac{1-Q/A}{RPS.C}$

Where:

RPS = revolutions per second of the highest speed disc.

c = counts (quanta) per revolution of the high-speed disc.

Q/A = manufacturing tolerance applied to minimum quantum width.

In a non-linear encoder, then:

$$C = \frac{360}{\text{Angular length of smallest quantum (degrees)}}$$

Q/A can be assumed to be 0.5 if no other tolerance is specified. Q/A should, however, be specified with typical values ranging from 0.25 to 0.10. The same manufacturing variations that affect transition accuracy affect Q/A, except eccentricity is not as important. V-scan or U-scan encoders have a smaller Q/A than monostrophic encoders. On the other hand, the timing requirements for U-scan or V-scan are more severe.

5.6.3.6 Polystrophic codes. Encoders using polystrohpic codes such as natural binary require sampling circuits which provide non-ambiguous outputs in a form directly usable by peripheral digital equipment. U-scan encoders such as the configuration shown on Figure 67 typify the sampling requirements for polystrophic encoders which need much less translation circuitry, but do require certain basic sampling logic. The minimum logic circuitry shown on Figure 67 has three basic disadvantages:

a. Momentary ambiguous outputs occur.

b. Encoders cannot be paralleled.

c. No noise suppression is provided.

Momentary erroneous outputs will result if the 2^0 bit is not stored before storing the 2^1 and other higher order bits. A time delay must be provided after storing the 2^0 bit to provide for charging the capacitance to the output cables. If two or more encoders are operated in parallel, both C_{lead} and C_{lag} of the unselected encoder must be deenergized.

5.6.3.6.1 Latch-follow-store logic. A more sophisticated logic network is shown on Figure 68 which utilizes the follow-latch-store control, a technique which provides more flexibility in application and improved reliability. The encoder modes listed in the truth table on Figure 68 are defined as follows:

a. Follow: The condition where the output of the circuits reflect all changes of the encoder contacts.

b. Latch: A condition where any encoder contact closure is stored and further changes are not recognized.

c. Store: The condition where changes of the encoder contacts have no effect on the data retained in the selection circuits.

d. Inhibit: All bits are equal to zero.

5.6.3.6.1.1 Sequence of operations. Typical applications for a latch-follow-store circuit are digital recording systems and digital servo systems where data is read into a recording device or storage register. Normally, the sequence of operations would be in the following order.

a. Follow mode: The encoder output continuously follows the angular shaft position, and the output is available in a form suitable for light bank display or for continuous feedback in a servo loop.

b. Latch mode: The selection circuit stores the output of the encoder sensors, disregarding noise transients or mechanical variances such as shaft oscillation or momentary contact bounce.

c. Store mode: The output does not change even though the input variable may continue to rotate through a limited tolerance angle. If the tolerance is large requiring storage for longer periods of time, latching storage registers may be required for all bits. The tolerance angle can be converted to time by determining the quantum time (Q) at the maximum interrogation speed and taking a percentage of that figure. The percentage of quantum time depends on the manufacturing tolerance, typically equal to one-fourth the minimum quantum time (Q/4).

d. Inhibit data: To prevent the commutation of current when the encoder is not being interrogated or to select parallel encoders for interrogation, the encoder output is temporarily disabled.

Latch-follow-store circuits are usually packaged as an integral part of an encoder system to provide maximum flexibility within a self-contained package. However, for certain system applications, these logic processing circuits can be designed to be employed separately.

5.6.3.7 Timing circuit. Timing involves certain circuit design principles rather than the design or selection of discrete hardware items. Both the absolute and the relative timing aspects of the logic networks design must be analyzed and evaluated to ensure: (1) the required sequence of circuit operations will result, and (2) the resulting sequence will fulfill performance requirements.

5.6.3.7.1 Timing in in V-scan or U-scan encoders. Consider the timing problem in V-scan or U-scan encoders. The selector bit must be stored before the output of higher order bits are stored or used; otherwise the selector might change in the middle of a storage interval. If this should happen, the lead sensors, for example, might be connected to storage for the first half of the storage interval and the lag sensors would then be connected during the second half. If the count were changing from 011 (lead) to 100 (lag), the stored value might end up being all ones (111), all zeros (000), or any random combination. The time to store the least significant bit plus the time to store the next most significant bit (or bits) must be less than:

$$\frac{1/2 - Q/A}{RPS \times C}$$

This interval is always less than one-half T_c and two storage actions must be completed in this minimum time interval. Therefore, it follows that filtering is less effective in encoders using V-scan or U-scan as the anti-ambiguity feature than in encoders using Gray code or cyclic decimal code. In either case, timing is critical and must include provision for the time required to charge the capacitance of the associated cabling.

5.6.3.7.2 Hybrid coding. If hybrid coding is used (for example, the most significant monostrophic bit on the high-speed disc is used to select lead or lag commons of a polystrophic code on a low-speed disc), the selector bit must be stored before the output of the low-speed disc can be stored. It is not unusual to overlook this design principle since the probability of the selector bit changing during readout is small, equal the ratio of the sample pulse length to the time required for one-half revolution of the high-speed disc. Timing and control of the storage sequence is not critical if monostrophic codes are used on all discs. With V-scan the reverse is true, and all bits must be timed to store in correct sequence, least significant bit first. An alternate method is to store the output of all sensors, both lead and lag; however, this approach doubles the requirement for storage capacity.

5.6.3.8 Conversion circuits. Conversion circuits are used to modify or translate the outputs of encoder sensors (contacts, heads, photocells, and so on) to a required form, adequate for processing, display, or computing equipment. The sampling, selection, conversion, storage, and output functions are often performed by a common, integrated circuit or network with groups of components accomplishing multiple logic processing tasks. This makes it difficult to separate individual functions along purely hardware-oriented lines. Conversion is often necessary or desirable because a particularly attractive scanning method is used to avoid ambiguity, or because the selected scan is most ideally suited to the encoding task insofar as the detection function is concerned. As discussed in earlier chapters, the outputs produced through non-ambiguous scanning or coding are often in a form that is not suited to the needs of the parent system or the equipment which must receive and further process the encoder output.

5.6.3.8.1 Excess-3 conversion. A typical example is an encoder using an Excess-3 decimal code. This code has the advantage of being non-ambiguous, producing a natural nine’s complement, and having a convenient, balanced pattern. Often it is necessary to translate an Excess-3 code sensor output to natural binary form for certain applications. A network for accomplishing this task is shown on Figure 69. This network performs the Excess-3 to natural binary conversion using an up-down count which can be produced from a standard encoder disc owing to the complementing feature of Excess-3 code. An extra track is needed to provide polarity (+ or - sign) and this feature can be easily provided.

5.6.3.8.1.1 Truth table for Excess-3 code. Table XIII is a truth table for the individual stages of Excess-3 to natural binary conversion process showing the states of the binary values at each step of the progression. Table XIII shows that for one decade (0-9):

$$a = \bar{A}$$

$$b = \bar{A}B + A\bar{B}$$

$$c = ABC + \overline{BC} + \bar{A}B\bar{C}$$

$$d = CD + ABD$$

These logic equations establish the gating conditions for the conversion network. The resulting network, shown on Figure 69, implements these requirements. Complements of the digits are provided in the initial circuit stages, and actual conversion is accomplished in the final stages. The typical conversion process shown in Table XIII is but one of many possible translations that may need to be implemented for a specific encoder application. The basic technique of defining the overall translation requirements, developing a truth table, deriving the gating requirements in the form of logic equations, and then implementing a network that satisfies the equations is equally valid for all conversion tasks.

5.6.3.9 Selector circuits. Selector circuits are used for sensor switching and sequencing in encoders and are, perhaps, the most universally required and widely employed of all logic processing networks. In this section a number of common, typical selection circuits and networks are discussed to provide some practical examples of how basic selector circuit principles are applied in analyzing requirements and in the design or selection of appropriate logic processing elements.

5.6.3.10 Set-Reset selector circuit. The Set-Reset selector circuit is used when two selector tracks are available on the encoder disc: one track for the LSD (2^0) and the other is the complement of the first ($\overline{2^0}$). Thus, when the 2^0 track is On (True), the $\overline{2^0}$ track is Off (False) and vice versa. Since it is not possible to design an encoder so perfectly that a change in state on both tracks can be sensed simultaneously, the tracks are intentionally time-phased to overlap slightly so that for a short period both tracks are On. The 2^0 track is defined as the Set track, and the $\overline{2^0}$ track is the Reset track. Table XIV is the truth table for the Set-Reset selector circuit. As shown in the truth table, the selector circuit must be supplemented so that if the 2^0 goes On, even momentarily, the circuit must store the True state until the Reset track goes On and the Set track goes off. In the truth table (Table XIV), Q_t is the instantaneous, present value of the output and Q_{t-1} is the previous value of the output. The present value of the output is independent of the previous value of the output except when both inputs are zero. When both Set and Reset are Off, then the present value of the output is equal to the previous value. A logic circuit that meets this specification is shown on Figure 70 which implements the following logic expressions:

$$Q_t = S \text{ (stored value of } Q_t\text{)}$$

$$S = 2$$

$$\overline{Q_t} = \overline{2^0}$$

Q_t can be used to drive the lagging common and $\overline{Q_t}$ to drive the leading common of the next higher bits. The timing relationship of Q_t to the input signal is shown on Figure 71. External control can be added, thereby establishing the operation of set-reset selector circuit as shown on Figure 72. The selector circuit control functions are summarized in Table XV. When the Encoder Select is Off, both Qt and Q_t are Off and all outputs from the encoder are zero. This permits the outputs from several encoders to be connected through diodes to a common bus. It is not necessary to employ the Encoder Select control or the associated inverter and OR gate unless encoders are to be operated in parallel into a common bus. Control line A determines whether the selected encoder output follows the instantaneous shaft position, or whether the selector circuit output is stored corresponding to shaft position at a specified time. The set-reset selector circuit can be considered a latch circuit that is reset automatically by a special reset track. Another set-reset selector circuit that is often used for inter-disc or inter-belt selection in U-scan encoders or similar multi-turn devices is shown on Figure 73. Table XVI is a truth table for_this circuit implementation. Usually, s drives $c_{lead}2$ and S drives $C_{lag}2$ directly. In some applications the additional amplification provided by the inverters is required to drive the output load. In addition, the latching action of the feedback circuit prevents noise from the high-speed disc interfering with the output of the low-speed disc. This is of special advantage in a high-speed servo where the low-speed disc is used to select slow-down points.

5.6.3.11 V-scan selector circuit. A typical selector circuit for switching sensors in a V-scan encoder is shown on Figure 74. Used extensively in control systems, V-scan encoders offer particular advantages where several encoders are to be scanned serially. However, there can be serious limitations in reliability. The circuit shown on Figure 74 is a typical sampling circuit for V-Scan encoders. The sequence of operations for the circuit shown on Figure 74 is as follows: An encoder common is selected, thereby gating bit information to the input AND gates. Starting with the least significant bit (20), each bit is gated for one time period (T_1, T_2, and so on) into lead-lag gates G_1 and G_2. At the end of each bit time, the clock pulse allows the correct bit to be set in flip-flop F1. If the bit previously stored in F1 is a binary "0", then AND gate G_1 is satisfied, thereby selecting the leading encoder track to be stored. Inversely, if the bit in F1 is a binary "1", AND gate G_2 enables the lagging encoder track to be set in F1. This selector logic has the advantage of providing a serial binary output least significant bit first. Where high rotational speed is required, this V-scan technique allows a longer time period to scan encoders serially. A major disadvantage derives from the fact that if the encoder data is entered serially into the system, the system's logic is limited by the rate at which it can accept information without a buffer register. This occurs because the bit interrogation time at high clock rate can be of insufficient duration to determine the contact state reliably.

5.6.3.12 Logic systems. For maximum reliability each bit should be stored in a latching register. A typical high reliability logic system is shown on Figure 75. This system utilizes several U-scan encoders in parallel. Using U-scan encoders in the multiple configuration shown on Figure 75 reduces the effect of noise transients, contact bounce, cable capacitance and current commutation. With these factors minimized, the encoder system will provide the greatest possible reliability. The sequence of operations for the logic system shown on Figure 75 is summarized in Table XVII.

5.6.3.14 Driver circuits - purpose and function.. Driver circuits are required in digital encoder systems to perform the initial stage of sensor selection, and to provide sufficient signal power to drive the encoder output line. In encoders using self-selecting scans, for example, the sensor-select function is usually performed by a driver circuit under the control of the LSD. Drivers of this sort can be designed and implemented in one of two configurations--negative interrogation and positive interrogation. The implementation of selection logic is discussed in 5.6.3 in functional terms.

5.6.3.14 Driver circuits - description analysis. Driver circuits can be packaged as an integral part of an encoder unit, or modular units external to the encoder can be used. In either case, the function and basic operation are the same. The circuit implementation shown on Figure 76 is a typical external drive circuit module designed to provide selection logic for a brush contact encoder using self-selecting scan and negative interrogation. Figure 77 shows the same basic driver circuit modified for positive interrogation. Basically, the encoder driver consists of a two-transistor, regenerative Schmitt trigger input stage followed by two cascaded line driver amplifiers. The regenerative input circuit is controlled by the switching action of the encoder LSD track. The output from the line driver amplifiers is the digit and complement of the LSD and is normally used to control both the leading and lagging sensors in the following digit and to provide LSD output to the encoder load. This circuit provides isolation of the output and ensures that encoder load current is not switched by the commutation of the LSD track. Figure 78 shows the typical envelope dimensions and packaging requirements for circuits of the type depicted on Figures 76 and 77. Table XVIII details a set of typical operating specifications. An example of a driver circuit which forms an integral, internal part of an encoder system is shown on Figure 79. In the example shown, the driver is a printed circuit board assembly consisting of dual differential amplifiers, shapers, and line drivers. The configuration shown on Figure 79 is implemented to service a 2000 count optical encoder. However, this design approach can also be used successfully with contacting encoders or with other non-contacting types. Figure 80 is a cutaway view of the encoder unit showing the physical location and arrangement of the driver circuit board.

5.6.3.15 External driver circuit - operating theory. In the typical external driver circuit shown on Figure 76, an open circuit in the LSD represents a logical “1” since the circuit is designed for use with a natural binary encoder, using negative interrogation and V-scan. To avoid ambiguity, the logic for sensor selection in a V-scan encoder ensures that if the LSB is logical “0”, the leading sensor is selected; and if the LSB is logical “1”, the lagging sensor is selected for the following digit.

5.6.3.16 Driver circuit operation. The signal is applied to driver input terminals five and six which are connected to the O and C contacts, respectively, of the encoder. When the O and C contacts are conditioned to produce an open circuit (logical “1”), transistor Q1 is On, Q2 and Q3 are off, and Q4 is On, causing the negative input voltage to be switched to the one digit terminal (lagging sensor) of the encoder via driver output terminal four. The LSD complement is 0 volts (logical “0”) since Q3 is Off. When the O and C contacts are conditioned to produce a closed circuit (logical “0”), Q1 is Off, Q2 and Q3 are On, and Q4 is Off. The negative input voltage is switched to the 1 digit complement terminal (leading sensor) via driver output terminal 3. The 1 digit is 0 volts (logical “O”) since Q4 is Off. All load current flows through the saturated emitter to the collector junction of Q3 or Q4. Operation of positive interrogation encoders (see Figure 77) is similar to that of negative interrogation units. The only difference is the reversed polarity of the internal diodes. Often interbit amplifiers are used to provide charging currents or to restore the dc level lost through the logic diodes. Where interbit amplification is required, special leads are usually provided for the addition of amplifiers between any two digits.

5.6.3.17 Integral driver circuit. In the typical integral driven circuit (see Figure 79), the output of each photocell is connected to dual differential amplifier stages, Q4-Q5 and Q6-Q7. Dual shaper stages, Schmitt triggers consisting of Q2-Q3 and Q8-Q9, receive the outputs of the amplifier stages and shape the signal to an approximate square wave. The square wave signal is used to drive dual line drivers, Q1 and Q10. The two-line driver outputs are symmetrical and 90° out of phase to one another. As shown on Figure 81, symmetry is defined as equal deviation and amplitude in the negative-and-positive-going excursions of the waveform. Symmetry is ensured by proper adjustment of variable resistors R17 and R18 which varies the bias voltage across the photocell output. This, in turn, controls the amplitude of the photocell output. Before R17 and R18 can be adjusted, a minimum output level (approximately +0.3V) must be available from the photocells. Photocell output is dependent upon the proper alignment of the excitation lamps and the adjustment of the excitation lamp supply voltage.

5.6.3.18 Driver circuits - comparative evaluation. The driver circuits described and discussed in this section are but two typical variations of the numerous internal and external configurations currently available. Beyond the wealth of standard modules and systems available as shelf hardware, there are infinite design possibilities to meet individual or unique performance requirements that are wholly within the limits of current state of the art. In designing or selecting driver circuits, the basic tradeoff considerations are space and performance. If space is limited, the internally packaged integral driver circuit is usually superior. Where circuit performance is the overriding parameter and space is not at a premium, the external approach is preferable. As in any problem of system engineering, however, the total system must be considered, and the driver circuit is only one segment of that system. Nonetheless, much can be gained in overall system effectiveness through the careful design and selection of the encoder driver. Some important circuit considerations are summarized as follows:

a. Logical “1” outputs should have a low internal impedance so output voltage levels do not vary with encoder shaft position.

b. If digit and digit complement loads are equal, the load will be constant and internal impedance will not be as critical.

c. Output load current should be capable of supplying 2 mA per bit over the temperature range and supply voltage conditions up to the capacity of the encoder.

d. The input current through encoder sensors should be limited to 500 microampere, and voltage across sensors should be under 10 volts for contacting types.

e. Logical “O” state should be less than 0.5 volt.

f. The two output states must always assume mutually exclusive states.

g. The level at which the output of encoder sensors change the state of the driver circuit should be greater than 1.5 volts.

5.6.4 Output mechanics.

5.6.4.1 Output circuits - purpose and function. The output functions in an encoder system (see 5.3) fall mainly in five broad categories: amplification, storage, shaping, timing, and conversion. These functions are not always exclusively an output task. Often the logic processing or detection hardware will also amplify or convert signals, store or time data, or shape waveforms. The major difference lies in the purpose behind the function. Output circuits are used in encoder systems to condition the digital signal for use by a parent system or peripheral equipment. Amplification may not be required purely as an output function since the signal strength established in earlier functions (for example, logic or driver circuits) may be wholly adequate to the subsequent output requirement. Similarly, an adequate waveshape may be developed as part of logic processing; output requirements may not include a need to store pulses for a unique output format. The circuits described and discussed in this section are typical of the kind of circuits commonly used for output signal conditioning. Many of these circuits and, certainly, the functions of these circuits can be integrated with other functional segments of the encoder system.

5.6.4.1.1 Flexibility. The use of special output circuits does provide a certain measure of flexibility in design and application, since the most efficient logic processing or detection technique may not always provide a signal with ideal output characteristics. Anti-ambiguity coding, scanning, and logic processing, for example, often require a sizable number of circuits. The problems of designing these circuits are substantially more complicated and demanding if the selection and logic processing chores must provide suitable encoder outputs without further processing. By considering output circuits separately, an increased measure of specialization can be achieved. This practice is also especially compatible with a modular design approach.

5.6.4.1.2 Cost effectiveness. Proper design and selection of output or interface circuits can also be a valuable tool toward improved cost effectiveness. A developed and proven encoder with the required performance characteristics (for example, capacity, accuracy, resolution) can be used in a unique system application. In such cases, the output should be supplied in a form readily adaptable to system needs by adding a suitable interface in the form of output circuits. The actual level of encoder reliability will then be known in advance, the time and cost of developing a completely new encoder system can be avoided, and the risk factor can be limited to a single untried element--the output circuits. However, before deciding to modify an existing encoder with an output/interface, a careful cost and performance analysis must be completed to ensure that this approach is, in fact, the best tradeoff. Such influencing factors as space and weight limitations, power requirements, maintainability, heat dissipation, and packaging problems must be considered.

5.6.4.2 Output - description and analysis. As with other electronic circuit elements of an encoder system, the output electronics can be included as an integral part of the encoder unit or may be packaged separately, external to the encoder. This design feature will depend on such variables as space availability, specialization, performance criteria, and power requirements. Either technique can perform as well as the other, all contributing factors being equal.

5.6.4.3 Output - pulse shaping. Encoder signals are not only binary, but the information content is limited to a low frequency band. The rate at which encoder data can change is limited to the maximum encoder speed, which in turn is usually limited by the maximum rate of change (velocity) of the phenomenon being encoded. It is possible to improve the signal-to-noise ratio (such as reliability) of an encoder signal by limiting the maximum rate of response (band width) of the associated storage or decision-making circuits to the maximum significant rate of change of the signal. In other words, the filter response should be slightly faster than the minimum quantum time.

5.6.4.3.1 Problems and solutions. This possibility for improving reliability can conflict with other system requirements. For additional reasons, it may be necessary to employ an ample interval that is small compared to the minimum quantum time. In this case the filter response must be somewhat faster than the sample interval. This problem can be solved by applying power continuously to a selector bit. This bit signal operates at a low signal level to avoid electrical erosion. The selector signal must be filtered and clipped and is used to drive a circuit that continually follows the value of the filtered signal until a sampling pulse is received. The sampling pulse may be asynchronous and it is not necessary to anticipate its arrival. When the sample pulse is received, the selector bit signal is instantly stored. This technique permits a long filtering time constant combined with a short sampling pulse. With the above described technique, a U-scan encoder is used and thereby ensures that the other bits are relatively noise free, because they cannot change state during the sample interval. In other words, there is no edge noise. Latching storage registers can be used on all other bits to further improve their reliability.

5.6.4.3.2 Encoder noise. The filter can also take advantage of the special nature of contact encoder noise. Most encoder noise is due to intermittent contact at the edge of a contact or (less likely) dropouts in the center portion of a contact. In other words, only True signals are noisy. The ideal filter responds quickly to a True signal, but discharges relatively slowly when True changes to False. If the critical time constant is X, then the charge (response to True) time constant should be in the order of 1/40(X); and the discharge (response to False) time constant should be in the order of 1/4(X). The critical time constant, X, is defined as 1/10 to 1/4, the minimum quantum time, or about one-half the sample interval, whichever is smaller. Filtering alone is not particularly useful. The major advantage of filtering is obtained by combining filtering with clipping. This is illustrated on Figure 82. A typical filtering and clipping circuit is shown on Figure 83.

5.6.4.4 Output amplifiers. Output amplification for encoder signals is commonly provided by dc differential amplifiers which can be integrally packaged with the encoder unit or supplied as an externally-mounted printed circuit card or integrated circuit. Typical circuits of this type, as shown on Figure 84, can process from one to eight or more channels per circuit board, and circuit boards will optionally include amplification with or without polarity inversion. Thus, the options may include straight amplification or inversion, or an emitter follower output. A typical output impedance value is 1.5 kilohms with a positive or negative 5 volt, 12 mA high signal and a 0 volt low signal. Typical regulation characteristics are approximately 3 percent with around 0.5 percent maximum ripple.

5.6.4.5 Storage, timing, and conversion. The timing, storage, and conversion functions are most commonly accomplished as part of encoder logic processing or by encoder driver circuits (see 5.6.3.13). However, in some cases, notably in applications where time-sharing is required for using a number of encoder units to form an encoder system, output circuits will not only provide final signal conditioning, but will serve as the means of applying interrogation signals.

5.6.4.5.1 Sample configuration. A possible system configuration of this sort is shown on Figure 85. The encoders shown in this example are hypothetical, 10-bit, V-scan contacting units each requiring 20 output leads (19 contact wires plus one common wire). By providing interconnections as shown on Figure 85, the sets of 19 leads from each unit are tied together, thus minimizing the total number of leads entering the interfacing computer. Once this interconnection scheme is established, additional encoder units can be added using only one new common lead for each additional encoder unit. One external, time-shared scan matrix is required per system. Internal isolation diodes in each encoder are required for the time-sharing function, and corresponding leads from each encoder unit are tied together and connected through a bus to the scan matrix. Each encoder is interrogated by energizing its common line, applying voltage to the detection function within the encoder. With the interrogation signal applied, only one encoder exerts any effect on the scan matrix since all encoder outputs are effectively processed through common OR logic. The common signal is mechanized by processing the encoder selection signal in an inverting amplifier of the type shown on Figure 86. In this hypothetical system, the following basic characteristics of an efficient output design are demonstrated:

a. Data outputs are available on demand.

b. Each encoder acts as a randomly accessible memory cell.

c. All output electronics are digital and time-shared.

d. A single common lead to each encoder unit transmits the interrogation signal.

e. Outputs are presented to the parent system in a directly compatible form.

5.6.4.5.2 Other configurations. There are many other equally efficient output possibilities that can be used to meet a wide variety of system requirements. Constant real time outputs can be provided representing the instantaneous shaft position. This option, though, is not readily adaptable to the time-sharing concept. A compromise solution is to combine the approaches and use latching or storage circuits in conjunction with the interrogation technique to provide continuous on-demand outputs. Using this combination method, an interrogation signal is used to sample the encoder output l The resulting value is stored in a holding circuit and provided as a continuous output. Each subsequent interrogation results in a new output sample which is stored providing an updated continuous output value. This technique is called sample and holds; it combines the advantages of timesharing and random access with the benefit of continuous output. As with other optional design features, actual configuration depends on specific application requirements. The three basic output options are:

a. Continuous.

b. Demand.

c. Sample and hold.

5.7 Testing and evaluation.

5.7.1 Test requirements and criteria. To verify correct encoder system operation, units must be tested and evaluated against performance specifications and configuration requirements. These procedures serve as the final, ultimate design review and validation. They are also a means of assuring that the design has been faithfully and effectively translated into hardware during the manufacturing process. A number of tests are required at the various stages of encoder development: production, acceptance, and operational employment.

5.7.1.1 Mechanical and electrical tests. Generally, each of these various stages and levels of testing and evaluation consists of a number of mechanical inspections and a series of detailed electrical tests. The mechanical checks verify that specified manufacturing tolerances have been observed, that overall configuration is correct, that mechanical performance meets all requirements, and that the unit can withstand the anticipated operating environment. Electrical testing must validate correct count sequence, specified translation, bit width accuracy, minimum edge noise, and dropout error. Taken together, the mechanical and electrical test procedures must ensure that the instrument error is limited to about the same magnitude as the inherent quantization error. This requirement must be carefully specified and then checked through testing. In applications involving a large number of readouts, a statistical specification of encoded error is commonly used. The standard quantization error combined with the standard deviation of instrument error produces the standard deviation of total encoder error. This figure is ideally less than quantization error alone, but it must be specified individually for each distinct encoder design. Table XIX details the mechanical and electrical test procedures which must be performed as a minimum validation requirement.

5.7.1.2 Special purpose encoders. Additional checks will probably be needed for a particular encoder design; especially if the performance levels have been developed for a special purpose. The various levels and stages at which testing must be performed include in-process testing, acceptance testing, reliability testing, environmental testing, and system testing complete with integration and interface validation. The sequence and interrelationship of these test stages are shown on Figure 87.

5.7.2 Quality assurance methods. Detailed in-process inspection and test at each stage of manufacture are essential to assure encoder quality. Although the details of design and manufacture will, of course, determine the exact procedures and their sequence, the generalized quality assurance sequence shown on Figure 88 is common to most encoder types. In addition, a large body of preliminary qualification testing is necessary to ensure that parts, materials, and processes used in the encoder will yield the required performance. These requirements must be in exact, measurable terms and data inspected to verify compliance.

5.7.2.1 Preliminary assembly and inspection. Prior to assembly, all piece parts are inspected and then brought to an assembly area. During initial assembly, the various encoder pieces (disc, sensors, sensor plates, body parts, bearings, gears, shaft and so on) are assembled. A thorough check of dimensions, tolerances and clearances must be performed, as well as a general surveillance of workmanship. If gear trains are used, they are assembled during the latter stages of initial assembly. It is also usual to assign a lot identification number to each unit at this point to provide a means of tracking each individual unit through the final stages of assembly to completion.

5.7.2.2 Electronic assembly. When preliminary assembly has been completed, the unit is ready for electronic assembly and wiring, which usually includes a certain amount of soldering. Since fluxes which vaporize during the soldering process will contaminate an otherwise clean area and the encoder unit as well, special care is required to protect both the assembly area and the interior of the unit from contamination. After soldering, the unit may require ultrasonic cleaning, especially if soldering is done outside a clean area. Quality assurance procedures should include careful checking and control of contamination and detailed checks to ensure correctness of wiring and proper installation of diodes and other electronic components. Special checks are needed to ensure that polarity is correct where this factor is critical (diodes, capacitors, and so on).

5.7.2.3 Final assembly and alignment. The encoder is now ready for final assembly and alignment. These processes must be accomplished in an antiseptically clean environment. Laminar flow benches located in carefully controlled clean rooms are essential to provide the required degree of cleanliness. Quality assurance during this final phase involves at least as much checking of the assembly environment as of the encoder unit itself. Assembly personnel must be trained and skillful in clean room techniques and continuous monitoring of personnel performance and techniques is a must. Parts must be cleaned ultrasonically before being brought to the clean room in dust-tight containers. During final assembly, sensors and discs are aligned, electronic subassemblies are installed, and the enclosure is secured. A final check of workmanship and proper method should be made before the encoder is enclosed. Some encoders which require a preliminary run-in to stabilize wear conditions must be thoroughly cleaned after run-in and then given a final quality assurance inspection and check.

5.7.2.4 In-process inspections. The essential feature of any quality assurance program for digital encoders is the use of a series of exacting, incremental in-process checks throughout the manufacturing, assembly, and alignment of each unit. Imposing a requirement of this sort as a separate process would contribute to substantial increase in the cost of an encoder. It is, therefore, important that the manufacturer include the required degree of quality assurance as an integrated portion of the manufacturing process. This is true of most encoder firms, especially those producing units for military or aerospace applications. Commercial grade encoders do not require as much in the way of careful manufacturing control and are rarely built to the same exacting standards imposed for most military uses. In the design and selection of an encoder, these facts should be kept in mind when specifying requirements, to ensure that cost and excellence are both considered and traded off against one another.

5.7.3 Mechanical inspection. Regardless of the level or stage of testing, certain mechanical inspections are required. For obvious reasons, it will be more practical to accomplish certain of these checks early in the assembly process. However, if later functional evaluation discloses faulty operation, the mechanical tests and measurements may have to be repeated to identify the cause of the fault and to avoid repeating a mistake in the assembly or manufacture of subsequent units. As with all electromechanical devices, basic dimensional inspections can be accomplished by normal inspection techniques. Since encoders are basically a rotating shaft device, special concern must be given to the shaft characteristics. In addition to normal dimensional checks, the following checks deserve special consideration: shaft end play, shaft radial play, shaft runout, shaft perpendicularity and concentricity, and shaft torque.

a. Shaft end play is the motion of the shaft parallel to the encoder major axis while the encoder is held stationary. This end play can be accurately measured by using a dial indicator and precision force gauge. Insufficient shaft end play can result in early excessive bearing wear.

b. Shaft radial play is the motion of the shaft which is parallel to the encoder face while the encoder is stationary. A standard precision dial indicator is adequate to record shaft radial play.

c. Shaft runout will determine the straightness and uniform diameter of the shaft. This check can be satisfactorily evaluated by using a dial indicator and obtaining the difference between extreme indicator readings.

d. Shaft perpendicularity as referenced to the encoder code disc can directly affect shaft torque (both starting and running) and bearing wear. It must, therefore, be checked to ensure proper encoder operation. A shaft that is non-concentric will cause errors.

e. Shaft torque can be accurately measured by a torque watch. The most common factors contributing to excessive torque (either starting or running) are inadequate bearing tolerances, excessive brush to disc contacting forces, inadequate disc lubrication, and non-perpendicularity of shaft to disc. Measurements derived from performing torque tests establish a standard by which average contact force can be measured.

5.7.4 Electrical tests.

5.7.4.1 Electrical testing - general. The electrical testing and functional checkout of an encoder can be accomplished by a number of different and equally valid methods. The particular method chosen depends on the actual design and intended application. However, the method selected must ensure qualification and acceptance as set forth in the controlling specifications, which should also state the test method as well as the performance criteria. Several generally accepted testing procedures are described below.

5.7.4.1.1 Light bank display. A simple, yet effective, method of checking the count sequence output of an encoder is to display each bit on a light bank. Due to the current and voltage limitations of brush type encoders (such as 30 VDC, 2 mA noninductive load during rotation), an amplifier must be used to drive the lights. A typical circuit for such an amplifier is shown on Figure 89. This method is useful only when testing the output count sequence for master errors and such. When checking the encoder output count on a light bank, the encoder is rotated by hand. The light bank check is quite inadequate for testing bit width tolerances, transition accuracy, dropout (bit error) or edge noise.

5.7.4.1.2 Printout. To eliminate the manhours required to read a light bank, the encoder shaft can be connected to a low rpm motor. The encoder output is then translated to decimal and connected to a digital printer. To prevent misreading during transition times, store-follow or latching logic should be used. The printed tape can easily be read. As with the light bank display method, printout of the encoder count tests only for the correct count sequence. The advantage the printout method has over the light bank test method is that a permanent record is provided in the form of a printed tape.

5.7.4.1.3 Recording oscillograph. An excellent method for displaying the entire count output of an encoder (not sampling) is to use a recording oscillograph. The best results are obtained with oscillographs which use direct writing, light-sensitive photographic paper. The encoder output count is displayed on a paper roll as a series of traces (see Figure 90) for a natural binary code. Since galvanometers used with photographic type oscillographs are low current devices, a resistor in series with the galvanometers is the only requirement necessary to interrogate the encoder output count. The resistor value is determined by the type of galvanometers used and the deflection desired. Since galvanometers are relatively expensive, a transistor buffer is recommended to prevent damage due to miswiring or shorting of the encoder test equipment interface. A typical buffer circuit which reduces the current through the encoder contacts when driving both a galvanometers and lamp bank is shown on Figure 91. Tests have shown that noise bursts of very short duration (10 microseconds) can be clearly detected with oscillographs using a buffer circuit like the one shown on Figure 91 and a galvanometers with a flat frequency response of 5 kHz. The general notion that oscillographs are not effective monitoring devices at high frequency is not applicable for encoder testing. By translating the encoder output to decimal or octal prior to entering it to the oscillograph, several advantages are obtained:

a. Fewer galvanometers are required.

b. More bits can be displayed on the same size paper or smaller paper can be used.

c. Reading errors are less likely when interrogating the oscillograph output.

Figure 92 shows the typical staircase trace recorded by an oscillograph when the input is in decimal notation. Any miscount can easily be detected by a sharp discontinuity in the staircase pattern. Any invalid code is indicated by a step position not in keeping with the established staircase pattern. When plotting encoder output for 8421 BCD or natural binary codes, the least significant bit (2^0) changes every count. This change can be recorded in addition to the staircase transition traces, and is useful when reading the oscillograph output to determine the least significant bit width (minimum quantum). For unit distance codes, no single track can be displayed for count width. To assist in reading the oscillograph plot, a special track can be recorded in addition to the encoder output count. This special track is defined as the unit distance bit and consists of a series of cascaded exclusive OR gates which sample the encoder output to determine whether the total number of bits On is odd or even. In this manner, regardless of the bit changed to increment the encoder output count by one, the unit distance bit will detect the change. Figure 93 is a typical graph containing a unit distance bit and a staircase plot for an encoder output as recorded in octal notation.

5.7.4.1.4 Testing - comparison techniques. One of the most effective procedures used to check encoders for dropout errors is comparison. Although many techniques exist, the method which has come into its own within the last few years is to compare the encoder output to itself. This type of checking is extremely effective when testing for dropout errors. The basic concept consists of storing the encoder count and comparing the stored data to the actual encoder output itself. should the encoder count change during the store (comparison) period, a dropout error exists. This method of testing is defined as autocorrelation. External circuits required for comparison checking should include at least the following:

a. Clock control logic.

b. Storage circuits.

c. Comparator.

d. Encoder drive mechanism.

e. Counter (to tally error count).

Timing circuit requirements are governed by the type of encoder under test. For example, some encoders employ internal latch control circuits which provide continuous output count data for a predetermined time period. This type of encoder must feature either self-selecting V-scan or U-scan techniques. The “no change output count” period is determined by the maximum specified rotational speed for each specific encoder type. With this type of encoder, the timing requirements for the autocorrelator consist of a free running multivibrator and encoder latch control circuits as typically illustrated on Figure 94. The duty cycle for this circuit is approximately 90 percent. The store period is determined by the maximum encoder drive speed during the interrogation. For this type of test, worst case design must be incorporated in the timing logic; for example, the maximum store (compare) time cannot exceed the minimum “no count change” timing associated with the encoder under test at maximum rotational speed. No synchronization is required since, regardless of the test timing as referenced to the encoder, the encoder output is assured to remain in a stored condition for at least the maximum compare time.

5.7.4.1.5 Marker generator test. An excellent method for testing transition accuracy is to combine transition measurements with the code count and noise tests using an oscillograph. The encoder is geared to a special marker generator encoder using high precision gears. The marker generator encoder output is then connected to the oscillograph and is used to drive an external timing trace on the oscillograph. A typical trace is shown on Figure 95. Accuracy of better than 10 percent of a count can be achieved depending on the encoder being tested. The single major drawback to this method is that it requires a marker generator which matches the specific encoder under test. There are several methods available for determining the accuracy of an encoder output with respect to the shaft position. The method used should be determined by the angle to be measured, the number of encoders to be tested, and the manhours expended.

5.7.5 Typical test sequence.

5.7.5.1 Testing - general. The test procedures summarized in Table XIX and the test stages shown on Figure 87 form the basis for the broad majority of encoder test and evaluation programs. In a typical test sequence, mechanical and electrical checks are performed at each stage, data taken at each step, and the final array of facts reviewed and analyzed to evaluate encoder performance, validate the design approach, and verify manufacturing methods. The actual sequence of procedures and the details of methodology will vary from encoder to encoder. These factors must be selected and adjusted to suit the needs of each particular set of test and evaluation requirements. However, as a minimum, encoder testing should include the evaluation elements identified and discussed below.

5.7.5.2 Reliability testing. An encoder may operate with acceptable reliability in one system application and yet fail to do so in another system. Therefore, the test equipment should closely duplicate the interface conditions that will exist in the actual operational system. Provision for autocorrelation techniques should also be included. Each time the encoder is interrogated, the output should be compared against a standard. Any existing differences greater than one count in the least significant digit should be recorded as errors on a track-by-track basis. A budget for errors can be established after suitable study of overall reliability requirements. The test equipment can be programmed to signal if the error budget is exceeded, to make the decision as to the effectiveness of the encoder, to formulate the pass or fail decision, and to provide the means of mechanically driving the encoder input shaft. Then error budgets, which may be assigned as a function of shaft speed, can be easily correlated by the test equipment.

5.7.5.2.1 Automatic test equipment. Automatic test equipment can be used to determine accurately the performance and effectiveness of an encoder. When sufficient samples are processed, the reliability of the encoder can be established. Equipment of this complexity is necessary to establish firm data. Many techniques in general usage do not allow sufficient accuracy in transient error detection because they lack the resolution. Most important, many of the commonly used techniques depend upon subjective judgement by an operator. Oscilloscopes, indicator lamp banks, and strip chart recorders fall into this class. This class of equipment will point out repetitive errors. Therefore, it is useful in manufacturing processes and in performing an initial evaluation. When reliability testing is involved, however, automatic equipment will yield more accurate data.

5.6.5.2.2 Self-checking encoders. Some state-of-the-art encoders are capable of a valid self-check and can accomplish this function without interference with normal operation. Encoders of this type are organized internally in a manner such that two independent mirror image numbers are discretely developed as the shaft is turned. A second unique feature of this encoder is that all information is constructed from the least significant digit upward, ending at the most significant digit. With all outputs available from the connector, two methods of error checking are possible. The first method uses each output pair (true and complement) as inputs to exclusive OR gates. The outputs of all gates are connected to a single output to provide a signal whenever an error of any description is present. The second method employs a simple exclusive OR gate at the output (true and complement) of the most significant digit. If an error is present, outputs from the point of error to the most significant digit will lack the characteristics of mutual exclusiveness and an error indication will be produced. Consequently, errors can be reliably detected at the most significant digit because of the unique characteristics of the encoder. Error checking does not interfere with normal data flow in an interfacing computer, but performs in parallel and separate to the data. With encoders of the self-checking variety, the computer will have access to data and separate error monitoring in real time. As each encoder output is applied in sequence to a computer, the computer can assign weighting functions to the error signal since some functions are vital and require instant reaction if an error is present. Others are less important, and some random errors are tolerable.

5.6.5.2.3 First article testing. Other types of encoders are capable of varying degrees of error checking. The methods available for external logic and unit distance encoders consist mainly of storing the previously decoded work and comparing the present word against it digit by digit. This method is operable, but has the disadvantage of requiring a relatively large amount of computer time. The most common method of establishing reliability for encoders using external logic decoding or unit distance codes is through first article sampling and testing. Ideally, automatic test equipment is utilized to evaluate the encoders by autocorrelation. Encoder input circuitry in the test equipment should be identical to the system circuitry. Then the encoder will be tested under conditions of usage; and results can, with confidence, provide a measure of encoder reliability. This method is suitable for selecting encoding equipment from an array of candidate units in the process of gaining experience before the parent system is built. A logical next step is to test sample production units while the program is in the production phase. This time-proven method continually verifies quality while gathering reliability data.

5.6.5,2.4 Costs. Costs of reliability programs are eventually reflected in the final system cost. Encoder manufacturers normally use some automatic test equipment. Specifically designed equipment may be required for a particular program which will increase development and procurement costs. The test equipment is usually located at the manufacturer’s facility. It is often advisable for the user also to maintain some encoder test equipment if the system uses a sizable number of encoder units. However, reliability is just as important to the user of smaller quantities of encoders. The manufacturer’s experience with many systems is an excellent source of information. Recommendations as to speeds, voltages, and currents can usually be accepted with confidence. This information, combined with an effective system of quality assurance, will normally yield reliable encoder units without acquiring and maintaining a large and expensive test facility. If the test facility has been established and is available, it is best to rely on actual test data to determine and ensure reliability.

5.7.5.3 Environmental testing. The complexity of present-day encoders makes design proof-testing mandatory. Environmental testing must subject a sample unit to controlled stresses of the sort anticipated in an operating situation and must be performed under laboratory conditions to ensure proper control. Tests of this sort are sufficiently accelerated to generate the most meaningful body of data in the shortest practical time. these tests are varied and require specialized equipment operated by highly skilled personnel.

5.7.5.3.1 Cost effectiveness. As with reliability testing, verifying environmental resistance can be a costly process whether performed by the supplier or the user. Balancing performance with cost can be achieved by the use of carefully conceived and written specifications that assure the required degree of performance will be achieved and that over-performance is avoided. Cost effectiveness in this sense amounts to paying for the level of performance that is needed, but no more than that level.

5.7.5.3.2 Typical environmental tests. When shelf items are selected, often contractor’s certified data establishing qualification of the product on a previous program is sufficient proof of environmental resistance. However, with new units or standard units modified for a unique application, a new series of environmental tests are required. Most encoder manufacturers build encoders to meet established, specified standards of environmental resistance in anticipation of military and aerospace requirements. The time and cost of this testing will be absorbed by the total number of units manufactured to a given qualified design. The environmental factors most commonly investigated by testing include:

a. Humidity

b. Temperature

c. Thermal and mechanical shock

d. Acceleration

e. Vibration

f. Salt spray

g. Dust and sand

h. Barometric and hydrostatic pressure

5.7.5.3.3 Environmental extremes. Digital encoders can be designed and constructed to meet the most stringent environmental requirements. For example, magnetic encoders exist that can withstand a shock force up to 100 G’s while operating at speeds of 100 rpm. A well-engineered contacting encoder can withstand 25 G’s shock and operate effectively under vibrations ranging in frequency from 20 to 2,000 Hz with an input force of 10 G’s. Temperature effects, even in magnetic encoders which are inherently sensitive to temperature variations, have been overcome; and units exist that continue to operate successfully at temperatures ranging from -55°C to +100°C without requiring any external compensation in Core current. Units have been observed to operate indefinitely while submerged in boiling water without any cover or totally exposed to the elements. In recent demonstrations, two identical encoders were operated side by side from a common excitation source, but with one encoder in a controlled 100°C environment and the other held at 4°C. Outputs from the two units were observed to hold within 10 percent; it can be safely assumed that this performance could have been maintained even if the cold temperature had been held at a much lower level. Encoders of all types and categories have been successfully tested and used in every present-day environmental ambient, from relatively permissive industrial applications to the exacting requirements of shipboard usage and the ultimate demands of aircraft and space vehicles.

5.7.5.4 Acceptance testing. Each production encoder type must be formally checked against specified requirements to ensure that performance parameters have been achieved, and that valid testing has been conducted in the prescribed manner. The specification may result in a unique acceptance test sequence tailored to a particular system and unit. However, this practice should be avoided where standard, less individualized testing will suffice. Every encoder must be subjected to basic mechanical checks and inspections to ensure correct size, weight, torque, bearing runout, and rotational concentricity. This sequence of mechanical tests is followed by electrical tests which are more likely to involve special or system-oriented testing. The procedures commonly required for most units include verification of noise characteristics, alignment, count and conversion.

5.7.5.5 Edge noise There is a certain switching uncertainty inherent in all devices which must produce discrete outputs. Generally, switching transitions should be measured from the 10 percent to the 90 percent amplitude point on the rising wave front, and in the reverse order between the 90 percent and 10 percent amplitude points on the falling edge. The specific parameter to be monitored is the time duration of edge noise occurring during switching transition. The sum of all transitions occurring between a stable logical “O” and logical “l” condition in a small region (typically 10 percent of the pulse width) is defined as edge noise. As long as these do not exceed the nominal value of pulse width, no limit to their amplitude need be defined. Therefore, edge noise may take the form of a single transition from “O” to “l” and vice-versa. Alternately, it may be several 100 percent amplitude excursions. When presented in conventional fashion on an oscilloscope, the trace will normally be triggered from the encoder output and adjusted for a full cycle. The edge noise thus presented is the sum of all switching uncertainties. This will allow quick evaluation of encoder performance. Contributing factors included are edge noise, pattern linearity, and disc concentricity. All of these have first order effects on accuracy. This is particularly true of unit distance encoders where each transition individually affects accuracy. On weighted code (binary, BCD, and so on) encoders, only the least significant digit will affect switching accuracies. This test procedure should make use of as much automatic test equipment as possible to ensure rapid and accurate testing. In the design and selection of test equipment, special consideration must be given to the problem of angular velocity changes at the encoder input. To eliminate these undesirable changes, a flywheel or similar technique should be used.

5.7.5.6 Contact noise. Obviously limited to contacting encoders, this characteristic is defined as the effect of dynamic contact resistance changes induced by the action of sliding contacts. This parameter should be measured at the highest rated speed of the encoder. Typically, the noise level should be less than 100 millivolts for a 20-volt signal. This performance level is commonly achieved in carefully designed and constructed units by using gold surface plating on discs and contacts.

5.7.5.7 Alignment check. The alignment check validates the correct phasing of leading and lagging sensors in relation to the least significant sensor. Once established, it follows that the disc will count correctly since pattern accuracy, noise levels, and sensor array accuracy are known quantities. This check must be made at the highest speed of operation and checked in both directions. In multiple disc encoders, the disc-to-disc alignment must be checked by measuring the least significant lead and lag sensor position on the second disc in relation to the nonambiguous output of the most significant sensor on the first disc. This process should be continued disc-by-disc as required. This method takes into account all gear train accuracies and serves as a preliminary check of encoder count accuracy. Additional electrical checks which may be required include a voltage resisting test and diode performance checks.

5.7.5.8 Count check. Checking an encoder for proper count is similar to the test sequence described earlier as part of reliability testing. Automatic test equipment, usually most efficient and most accurate for this task, must be designed to operate the encoder at maximum speed, must duplicate interfacing circuits of the intended parent system, and must check the encoder unit for correct, accurate output count while the unit is in operation. If designed for bidirectional operation, the encoder should be periodically reversed to ensure equal rotation in both clockwise and counterclockwise directions. Error signals are monitored and registered in a counter with the entire checking procedure requiring approximately two hours per unit. A typical test sequence is used to validate output counts for encoders used in submarines. For example, this process operates each encoder for two hours at 200 rpm. Each encoder is interrogated 5,000 times per second. All outputs, true and complement, are individually monitored and compared for mutual exclusiveness at each interrogation. Any single lack of mutual exclusiveness constitutes an error and is automatically registered. The error budget is 100 errors for a two-hour test period and average results show 0-3 errors. Encoders checked to these standards and performing to these levels can be expected to give accurate, dependable service. Under a recent contract, 300 encoders, checked out as described in this section, performed in operating systems for over a year.

5.7.5.9 Transition accuracy test. Transition accuracy is defined as the precision exhibited by the encoder in switching count at some actual shaft angle, compared to the theoretical switching angle. An encoder counting in one-degree increments will characteristically switch at each degree of shaft rotation, plus or minus a small tolerance. This tolerance should not be larger than 0.25 the angular width of the least significant digit and will most often be around 0.10 of this angle. This test gives a total composite error for the encoder including all error sources, pattern accuracy, sensor location, disc concentricity, gearing errors, electronic rise time, and so on. Conversion accuracy is one of the most important tests performed on unit distance encoders. At present, this test is usually performed manually on a goniometer using a lamp bank for readout, with manual data recording. In unit distance encoders, the conversion accuracy is dependent on each transition, once, through the entire range of the device. Each transition must be checked for angular conformance to the specification since each one has the capability of being out of tolerance without relation to any of the others. One contractor was faced with the problem of providing a unit distance encoder (Gillham altitude reporting code) capable of producing 620 transitions per turn. Further specified requirements included a need to measure and validate accuracy at each transition. Six encoders were checked at all transitions. The resulting data was computer processed together with the error analysis for each encoder. The computer provided a set of 89 transitions which would confidently predict that a 3-sigma distribution of errors would fall within the test limits. Further development in this area is in progress and wider use of automatic methods for measuring conversion accuracy is not beyond the state of the art. Computerized and computer-aided methods will soon represent the major means for validating conversion accuracy replacing earlier, more rudimentary manual methods.

5.8 Research and development.

5.8.1 Performance problem areas. Digital shaft encoders provide a substantial increase in accuracy, resolution, service life, and reliability over the earlier analog devices that were formerly used to detect and quantify shaft angle or position. However, the digital encoders, like their predecessors, are far from perfect devices; they have their limitations. Even though the use of digital encoders has grown in the past few years, and even though this demand is on the increase, there are problem areas. These problem areas are receiving the attention of both government and industry, and the programs of research and development are yielding a constantly improving product. Problem areas exist in the mechanical, electrical, and logic design of encoder systems, which tend to limit performance, which in turn limits the total spectrum of possible applications. As the design and production problems are solved, the encoder field will broaden proportionately. As acceptance expands, competition and interest will sharpen with a resulting improvement in quality, cost and performance.

5.8.1.1 Availability of precision bearings. One of the major factors limiting encoder performance, especially in the area of accuracy, is the availability of precision bearings. At present, the degree of accuracy that can be achieved in producing encoder discs and disc pattern is wholly adequate in terms of the performance that can be expected from state-of-the-art bearing assemblies. As more precise and long-lived bearings are developed, a commensurate improvement in disc manufacture will be stimulated.

5.8.1.2 Contacting encoders. Presently, most encoders are of the contacting type, due mainly to the favorable cost relative to performance. Nonetheless, there is a definite limit to the resolution that can be achieved with commutator devices because brush-contact areas can only be reduced to a certain point. At the present time, a brush width of 0.004 inch is considered about minimum, and the narrowest and most useful commutator segment width is about 0.010 inch. Thus, about 256 conducting segments can be placed on a one-inch diameter disc. Commutators are usually produced by the photoengraving process, and the total accuracy within which segment edges can be controlled is 0.004 inch; for example, segment edges in a four-inch diameter disc would be accurate to approximately seven minutes of arc. Brush-alignment problems in a commutating encoder can prevent attainment of this level of accuracy.

5.8.1.3 Non-contacting encoders. The three basic types of non-contacting encoders (optical, magnetic, and capacitive) have been developed to circumvent the disadvantages of the brush-type encoder. However, the higher cost has restricted popular use of the non-contact devices; the cost of non-contact encoders ranges from three to six times that of the contact type for similar applications. In optical encoders there is a trend toward the use of low voltage DC-excited lamps because of the lower life expectancy of strobe lamps. Low voltage DC-excited lamps have a predicted life of approximately 10,000 hours. The resolution in reading an optical pattern is limited only by the wavelength of light. Diffraction does not become a problem until a viewing slit is made smaller than four microns, and then monochromatic light of very short wavelength can be used. A typical optical pattern made by photographic techniques has 65,536 opaque segments in an eight inch diameter. The segments are approximately 0.0002 inch wide and require the use of a lens type reading system. Greater line densities have been achieved where the resolution of optical patterns can approach 100 times that of an electrical commutator. At the present state of the art, the highest obtainable accuracy of optical patterns and associated reading method is one part in 262,144 (5 seconds of arc) for an 18-bit encoder.

5.8.1.4 Magnetic scan encoders. In magnetic scan encoders, the code discs consist of tracks of alternate magnetic and non-magnetic areas; each magnetic track is read out by a square-loop ferrite core positioned close to the surface of the coded disc. This reading head has two windings: a primary one for interrogation or excitation and a secondary one for signal readout. The proper electronic circuitry is, as usual, required to shape the encoder output so that unambiguous, pure binary signals will result. From a reliability standpoint, the main disadvantage is the life span of the encoder bearings, which is generally about 100 million revolutions. The resolution of magnetic encoders does not compare favorably with the optical types, but they are capable of higher resolution and life than the brush type device, since the index is not in contact with the patterns. Present resolution for magnetic heads is on the order of 0.0005 inch. Captive sensors, like the magnetic, require excitation by high frequency oscillators and some means of detection to resolve digital signals. Generally, this results in a more complex and, therefore, less reliable arrangement compared to photoelectric methods.

5.8.1.5 Minor problems. ther minor areas of concern which have been cited by both encoder users and manufacturers include the provision of substantially shorter propagation delays (10 nanoseconds as opposed to 50 to 100 nanoseconds), the need for tighter, more compact interior arrangement of electrical components, and the lack of standardization in user requirements. This last problem, diversified user requirement, is perhaps the most serious . Few encoders are developed as a standard item of shelf hardware in the usual sense. Many manufacturers have developed and maintain an array of production encoders in anticipation of user needs. Basically uniform devices are developed which almost always must be modified to a unique set of system requirements. This tends to raise acquisition and life-cycle costs since it is nearly certain that development costs will be involved in acquiring and using an encoder system.

5.8.2 Research - current programs. The constant present day process of development and encoder improvement is producing encoder hardware of better quality, high reliability and accuracy, and greater capability. Each of the problem areas is being investigated and time, money, and effort are being expended in an attempt to solve the problems. Shaftless encoders, Moire fringe devices, Ga, As, and IR encoders are examples of the solutions that are being provided. Many of the research and development programs are proprietary in nature while others are extremely specialized, such as those undertaken in response to a particular, unique requirement. It is significant to note that the bulk of progress in encoder development is the result of problem solving efforts directed toward a special user need. There are generalized programs of research aimed at improving encoder technology. For example, research into the use of Hall effect devices for magnetic reading heads has shown promise of giving an order-of-magnitude improvement in resolution for magnetic encoders. The use and manufacture of capacitive encoders is extremely limited for a number of reasons. Work is in progress for encoders that use capacitive principles, and a number of proposals for the development of such a type appear to hold promise for a device with good resolution. The technique basically incorporates a method for detecting variations in capacitance between capacitively-coupled discs which electronically generate an unambiguous binary output.

5.8.2.1 Microgon encoder. One of the common problems with encoders is that they, with their associated electronics, frequently occupy excessive space. An encoder currently under development is called the Microgon. It incorporates a new method of absolute encoding by combining a transducer with a resolution of 18 bits in a 38mm diameter package. the Microgon is a sturdy unit within a small frame size, yet meets the established criteria of high accuracy and rsoltuion. Conventional absolute encoders derive positional information by reading radially across a coded disc pattern. The Microgon uses the entire disc pattern, which is imaged on a specially developed Charge Coupled Device (CCD).

5.8.2.1.1 Development of the CCD. The CCD is composed of an array of electrodes capable of storing and transferring a finite amount of electrical charge. By placing the elements next to each other, such as in a ring, signals on the electrodes cause the stored charge to be passed from one electrode to the next. Since each stored charge may be of varying amounts, the ring of electrodes becomes a simple analogue shift register. The CCD can be considered to store analogue information until it is delivered, one increment at a time, as an electrical signal. The image-sensing function of the CCD utilizes a basic characteristic of silicon semiconductor devices. This is the photo-electric effect by which free electrons are created in a region of illuminated silicon. If a silicon device structure is created with a repetitive pattern of small but finite photo-sensing elements, a number of free electrons will be generated in each site. After an appropriate exposure time, the electron charge will be directly proportional to the amount of incident light on each site. If the light is a focused image of a disc pattern, the stored charges created in the ring of elements will be a faithful reproduction of the pattern projected on its surface.

5.8.2.1.2 Basic elements. The Microgon encoder consists of five components: a light source, disc, optics, CCD chip sensor, and an electronics unit. The light source and optics focus the image pattern of the whole disc pattern on the CCD. The disc has two concentric tracks: a pseudo-random binary track and a bar track which will form moire fringes by interacting with the CCD. The CCD is made up of a number of concentric rings of photo-sensing elements. These rings can detect the light pattern falling on them and can also shift the resulting signal around the ring, acting as an analogue shift register. The electronics unit controls the illumination and processing of the sensor signals. The unit contains the microprocessor logic which translates the sensor outputs as a shaft angle.

5.8.2.1.3 Principle of operation.

5.8.2.1.3.1 Patterns. “The light source is pulsed to enable the patterns on the disc to be imaged instantaneously on the CCD, resulting in a set of charges within the cells which represents the position of the pseudo-random pattern and the corresponding moire fringes. The CCD structure includes a feature to detect coincidence between the pseudo-random charge pattern and a defined reference position so that, by counting the number of impulses required to step the pseudo-random charge pattern round the sensor until the reference position is reached, the coarse angular position of the pseudo-random image, and hence the disc, can be determined.

5.8.2.1.3.2 Moire fringes. The bar pattern on the disc is imaged on the remaining tracks on the CCD, forming moire fringes with two light and two dark regions around each ring. It has been arranged that, as the disc rotates, related moire fringes move in opposite directions. If the disc is rotated, for example, by an angle represented by one of the previously defined steps, the moire fringes will move by the equivalent of 128 steps away from or towards each other, depending upon which direction the disc was rotated.

5.8.2.1.3.3 Resolution. By determining the relative phase between the moire fringes, the encoder is able to subdivide each angular increment by a factor of 128, providing a finer measurement of the disc position. Even higher resolution is obtained by interpolating between the steps of phase difference. Each of these further subdivisions is achieved by analogue processing techniques within the CCD."

5.8.2.2 Phasescan and Beamscan. Two innovations have been used to advance high-accuracy readout from photoelectric encoders: Phasescan and Beamscan. Layouts of these innovations are shown on Figure 96.

5.8.2.2.1 Phasescan. Phasescan was developed to provide outputs with resolution and accuracy on the order of one second of arc over 360° of rotating, using a single 14-inch disc rotating through one turn. Phasescan uses an absolute reading disc for a course reading and provides a vernier reading that allows fine data to be delivered from the least significant digit of the absolute reading code disc. Photoelectric sensors establish an accurate 0° and 90° phase relation from the basic high-accuracy pattern. By composing known encoder outputs of 90° phase relationships, it is possible to synthesize additional phasers to produce an X10 count from a disc having 129,600 increments (10 second-of-arc spacing). These phasers describe sinusoidal patterns as the disc is rotated and are individually fed into trigger circuits, which provide squarewave output in the time domain. These outputs are combined with the absolute-encoder data to provide a composite coded output.

5.8.2.2.2 Beamscan. The Beamscan has realized vernier outputs of up to 100 increments for each input cycle. By applying two wave forms of 90° phase relations to a cathode ray tube (CRT), a circular Lissajous pattern is described each time the input waveform completes one cycle. A segmented pattern of alternate opaque and clear sectors is placed over the circular scan, and the resultant light output from the CRT represents vernier data of the output. Photocells are used to digitize the light output. Using 129,600 divisions on the encoder disc and a pattern of 100 segments on the CRT, the Beamscan arrangement provides 0.10 second-of-arc increments, or one part in 12,960,000.

5.8.2.3 Other research. A research and development program is in progress to provide lighter, more compact encoders. One development program to produce an encoder housed in a single package, 1.1 inches in diameter and 2.0 inches in length, with a resolution of 8,192 divisions of 13 bits for one revolution has recently been completed. A coded disc, mounted as shown on Figure 97 on an input drive shaft, consists of 13 concentric tracks composed of opaque and transparent segments. The relative angular positions between the segments in the various zones are scanned with a radial index, and form a reflected binary code representing angular positions of the fixed index with respect to the disc. The photocells used in this encoder consist of cadmium selenite deposited in thin film form on a glass substrate and fabricated in a hermetically sealed package. The photoconductive cells are sequentially interrogated by applying a positive voltage pulse, in turn, to the most significant digit photocell, then the second, and so on to the thirteenth (least significant) photocell. The output of each cell as it occurs appears across a common-load resistor. The sensitivity of a reference cell circuit is adjusted so that the sum of the signals from the reference and code cells is positive with respect to a selected reference level of a one, and negative for a zero. Sequential interrogation of the photocells is accomplished by a diode matrix which consists essentially of 14 four-point AND gates, controlled by a four-stage flip-flop counter. The sequential outputs of the digit photocells are amplified by three feedback-compensated amplifier stages followed by an emitter follower. All these components are mounted in the encoder package.

5.8.3 Encoder of the future. In considering the future, more than digital shaft encoders are involved. The total process of converting an analog variable to digital signal promises to become increasingly important in the technical world of tomorrow. Thus, it is appropriate to discuss not only digital shaft encoders, but the wider field of digital transducers. Because of the many advantages of digital transducers, many research programs have been initiated in the field. A prime objective has been the development of a digital displacement sensor, since once a digital displacement sensor is successfully produced, the way is open for development of transducers for measurement of pressure, temperature, velocity, altitude, strain, and acceleration. Techniques explored include magnetic reluctance, optical rulings, and ring-lasers.

5.8.3.1 Magnetic reluctance. One of the early methods conceived to convert rectilinear displacement into a parallel pulse code used the magnetic reluctance technique. Digital signals were generated that represented a mechanical displacement of an electromagnetic armature by successively altering the state of a matrix of magnetically permeable wires or rods, as shown on Figure 98. The rods and associated sense windings form the matrix, which is positioned so that the ends of the rods are exposed to the magnetic field generated by the armature. The magnetic field is large enough to encompass the entire matrix regardless of the armature position. The sense windings are located on alternate rods and interconnected so that successive windings are opposite in polarity. When the armature is aligned with a rod containing the sense winding, the magnetic field about the rod is increased. This results in an increased magnetic induction and a strong signal in the sense winding about the rod. Positive and negative signals that are proportional to the magnetic field are induced in the sense windings on the remaining rods. The algebraic sum of these signals results in an output signal having the polarity of the strong induced signal, which corresponds to a binary 1. When the armature is aligned with a rod that does not contain a sense winding, the increased induction in this rod is not sensed, and the algebraic sum of the remaining sense windings results in a minimum signal output, which corresponds to a binary 0.

5.8.3.2 Optical rulings. An optical technique using rulings made of sections with lines and spaces similar to a Ronchi ruling involves a pair of optical rulings that cause a transmitted light to be modulated as one ruling is moved relative to the other. Each ruling is composed of sections having lines and spaces so that the number of lines per inch from section to section varies as 2^n varies. If n varies from zero to ten, an n-bit transducer becomes feasible by using a photosensing circuit to monitor the light transmitted through each ruled section. The master ruling design on optically flat glass 0.25 inch thick, would be a thin coating of silver deposited on one side, and the rulings formed by shaving away silver material. The rulings used in the transducer would be photographic reproductions of the master. The rulings are divided in half and the two halves folded against each other to form the ruling pair as shown on Figure 99. Each bit consists of two sections, each with its own photocell; the lines in both sections are parallel to one another, but they differ by 180° between sections. That is, the position of lines and spaces are reversed in the second section from that of the first. Therefore, since equal lines and spaces are used in the rulings, the signals from the two photocells are 180° out of phase, and a change in state is reached whenever the signals to the two photocells are equal. This method of using two photocells per bit has the advantage of being relatively insensitive to absolute light level when the two sections are illuminated from a common light source.

5.8.3.3 Ring lasers. The proposed optical digital transducer mechanical assembly is shown on Figure 100. The apertures for the ruled areas are illuminated with collimated light from an array of miniature tungsten lamps. An image of the appropriate lamp filament is formed on the surface of each phototransistor sensor. Optimum alignment of the filament image on the sensor is accomplished by a block of adjustable mirrors that alter the direction of the light rays from the rulings to the photocells. When completed in prototype form, the transducer will measure input position and convert this into a binary number proportional to the distance from a fixed zero reference. Test results indicate that a resolution of 50 microinches and an accuracy of 100 microinches could be maintained over the entire linear range. In 1963, the application of a traveling wave ring laser for sensing rotation relative to an inertial frame of reference was demonstrated at the conclusion of an extensive theoretical and experimental evaluation of various devices and techniques. An angular rotation sensor was envisioned that would not use moving parts and consequently would not be subjected to accuracy changes with time; it would be applicable in maintaining precise satellite orbits, measuring trajectory changes, space vehicle attitude, and orientation. The principles used in the research involved classical interferometer experiments where the effects of rotation on the propagation of light were studied by a modified two-beam interferometer arrangement, as illustrated on Figure 101, with the laser incorporated directly into the rotation sensor. Oscillation results from directing the waves around a closed optical path in opposite directions but along identical paths. The difference in frequency for the opposite directed waves is then related to the differential phase shifts for the rotating system, therefore, the best frequency obtained by optically mixing the CW and CCW beams is related to angular velocity of the system. The principle advantage of the ring laser over conventional interferometers is that phase changes, resulting from nonreciprocal optical path variations, can easily be observed as a difference between resonant frequencies. As a result, a semi-digital transducer becomes feasible.

5.8.3.3.1 Fresnel drag. Investigations into the use of the ring laser as a rotation sensor pointed to further application by using Fresnel drag to measure the flow of solid, liquid, and gaseous media. Fresnel originally postulated that light, in passing through a moving transparent medium, experienced a velocity change or a dragging effect. Experiments were conducted long ago to measure fringe shift by using flowing water and air; however, these experiments were handicapped by fringe shift detection capabilities so that large interferometer optical circuits and dense media moving at high velocities were mandatory.

b. By using the Fresnel drag effect with the ring laser to produce a frequency mode split, it has been possible to measure flow of solids, liquids, and gases. The ring laser used the 1.153 micron line of a He-Ne gas system in a meter square optical resonator, with gas tubes in three legs and with the fourth leg containing the moving medium to be measured. The applicability of these experiments to many areas of study, such as mass flow, density, and refractive index measurements external to a closed system, is quite promising. This permits obstructionless flow measurements, which are important where minimum pressure drop is desired and where corrosion and cleaning problems severely limit other techniques.

5.9 Number systems and codes. This section presents background information to aid in understanding encoders. It includes fundamentals of encoders, number systems, binary codes discussed by type, basics of Boolean logic as applied to encoders, and theory of code detection for the various techniques.

5.9.1 Number systems. Number systems are usually named by the base or radix used by the system. The base, in turn, determines the maximum number of individual digits available for use as a digit. A digit is defined as a character used to represent integers smaller than the base. In most common use and of most interest are the binary, ternary, octal, decimal, and duodecimal systems, with bases of 2, 3, 8, 10 and 12, respectively. These systems, then, have 2, 3, 8, 10 and 12 digits available for use. Table XX illustrates digit limitation for a given radix. Note that digit limitations do not limit maximum size of a number. Encoders utilize the binary system for digital output, while the readout is usually indicated using the decimal system. The remainder of this section is limited to discussion of these two systems.

5.9.1.1 Decimal system. In order to review number systems in general, consider the properties of the decimal system for values greater than zero. (Fractional values are not discussed in this handbook.) The decimal system uses a base of 10 and consequently, from the definition of digit, it has 10 individual digits (0, 1, 2, ... 9). Each digit position in a given number has a particular power (exponent) of 10 associated with it. The value of the exponent for any given digit position is equal to the number of digits to the right of the given digit. These exponent values form an increasing arithmetic progression when read from right to left (10^0, 10^1, 10^2, 10^3, and so on). In any digit position, the base and the exponent determine a weighing value for that particular position. Note that if the actual weighing values are computed from right to left, an increasing geometric progression is formed (1, 10, 1000, and so on). If the individual weighing value digit products are summed for each position in use, the value of a decimal number can be determined.

5.9.1.1.1 Example. To illustrate the foregoing, consider the decimal number 1,234. From right to left, the powers of 10 represented are 0, 1, 2, and 3 (10^0, 10^1, 10^2, and 103). The weighing values, or weights, are then 1, 10, 100, 1000; and the weighing value digit products are 4, 30, 200, 1000 l The sum of these products is 1,234. A summary of the steps is shown below. The value of having this computation in the familiar decimal system will become evident in later paragraphs.

5.9.1.1.2 Most significant digit and least significant digit. The digit in the position of the largest exponent in a given number (1 in the following example) is called the most significant digit (MSD), in that the largest possible error for a given number would be generated if it were wrong. Similarly, the digit in the position for the smallest exponent in a given number is called the least significant digit (LSD).

Digit		Base and Exponent		Digit		Weighing Value		Weighing Value Digit Products
4	x	10^0	=	4	x	1	=	4
3	x	10^1	=	3	x	10	=	30
2	x	10^2	=	2	x	100	=	200
1	x	10^3	=	1	x	1000	=	1000
								1234

1234: 1 = MSD, 4 = LSD

5.9.1.2 Weighing values in number systems. Weighing values in numbering systems are assigned with the conception of the system. Three classifications are used depending on the intended result (regularly weighted, arbitrarily, and non-weighted). In regularly weighted systems such as the decimal system, the weighing values are assigned by a mathematical concept such as arithmetic progression of exponents. This yields a geometric progression of weighing values since the base is constant. Knowing the mathematical concept, the value of a number in a regularly weighted number system can be calculated. In the arbitrarily weighted system, weighing values are selected to suit a particular purpose and no unchanging mathematical concept exists. Thus , to calculate a numerical value for a given number, the weights assigned to each digit position must be known. In the non-weighted system, digit positions are not weighted at all. To calculate a numerical value for a given number, a complete copy of the code assigned to each digit must be available.

5.9.1.3 Ten's complements. The ten's complement of any given number is that number which must be added to the given number to obtain a sum of 10 or a power of 10. The ten's complement of two is eight, since 8 + 2 = 10. Likewise, the ten's complement of 504 is 496 since 504 + 496 = 1000 = 10^3. The importance of the complementation property of a number lies in the fact that numbers may be subtracted by adding the subtrahend's complement, thus simplifying any computer techniques used to decode the digital output from an encoder. If the code used in any given encoder has the property of an easily formulated binary ten's complement, subtraction in the output electronics can be simplified to addition. In general, to find the difference between any two numbers, add the minuend to ten's complement of the subtrahend and ignore the MSD.

5.9.1.4 Nine's complement. The nine's complement is identical to the ten's complement previously described except that the figure nine is utilized and powers of nine are not. The nine's complement of three is six since 6 + 3 = 9. Likewise, the complement of 56 is 43 since 56 + 43 = 99. By utilizing the end-around carry, the MSD thrown away in the ten's complement subtraction can be used to arrive at the correct answer in nine's complement subtraction. Consider the subtraction problem 496 minus 387. Using rules similar to those for the ten's complement, we obtain the nine's complement of 387 which is 612. Adding, we obtain 496 + 612 = 1108. Removing the MSD from the previous result and adding it to the remaining number (end-around carry), we obtain 108 + 1 = 109, the correct answer. An encoder utilizing a code that is easily formed into the nine's complement is also useful in reducing external computer electronics if arithmetic subtraction is required.

5.9.1.5 Binary system. The binary system is a numbering system based on a radix of two. Only two-digit values are permitted, usually called zero and one. A binary number is a number using only two-digit values. (The digit value convention of zero and one is used throughout this handbook.) Binary numbers are formed as in the decimal system, by utilizing more digit positions. Various schemes called codes have been devised to utilize the properties of binary numbers. These codes (binary codes) are formed by varying the weighing value of weighing classification to suit the intended purpose. Regularly weighted binary codes are usually named by the four lowest integral weighing values. The number of possible codes is infinite; the number of useful codes, definable; and the more common of these, as they apply to encoders, discussed herein.

5.9.1.6 Natural bindary numbers. Encoders using a natural binary system (see 5.9.1.9) employ the simplest code for use in arithmetic or comparison circuits. (A comparison circuit indicates that A is greater than B or A equals B.) Natural binary is the most compact binary code since it requires the fewest number of symbols (bits) to represent any given span of numbers. It has no redundant or unused code combinations. Numbers coded in natural binary are most familiar to people working with computers or digital circuits. For shaft position encoders, natural binary numbers have the disadvantage of requiring the simultaneous change of more than one bit when transferring from one number to the next, as between 15 (01111) and 16 (10000). Although many techniques exist to cope with the ambiguity problem caused by simultaneous change, they add to the cost and complexity of the encoder.

5.9.1.7 Parity bits. Parity bits (tracks) may be added to permit automatic detection of errors. Numbers coded in natural binary have no redundant or unused code combinations. By adding redundancy, it is possible to detect or even correct some errors. A simple and useful redundancy is the addition of a parity bit. This permits detection of single errors. Odd parity occurs when a track is added to the encoder so that an odd number of contacts are conducting at every position of the encoder. Even parity is equally convenient to generate, such as an even number of contacts conducting at every position. This concept can be expanded to add one parity track for each group of contacts. For example, a fifth contact can be added to each group of four, so that of the total group of five contacts, either one, three, or five (an odd number) are conducting. Taken to the limit, 100 percent redundancy can be provided so that for every conducting contact, there is a non-conducting contact. This is the same as true and complement output. Parity bits permit automatic checking of the encoder operation and additional checking of subsequent data handling equipment. Variations on the basic binary number system are highly adaptable to electrical counting because all common electrical components are two-state (On-Off) devices. Although costly 10-state devices can be made for direct processing of the more familiar decimal number system, it is more convenient, efficient, and economical to perform storage, arithmetic, and logic operations in binary form and then convert the result to its decimal equivalent for display and human use. In the binary system all numerical values can be represented using only two symbols: 1 and 0. Thus, the 0 can be represented by an open circuit and 1 by a closed circuit, or vice versa.

5.9.1.8 Binary code 8.4.2.1. The 8-4-2-1 binary (natural or pure binary) code is a regularly weighted code and probably the most familiar of all binary codes. The natural binary code is similar to the decimal system previously described except that a base of two is utilized and only two digits are permitted. As in the decimal system, each digit position in a given number has a power or exponent associated with it, but the powers are exponents of the base two. The value of the exponent for any given digit position is equal to the number of digits to the right of the given digit. Similarly, when read from right to left (the standard in this handbook), the exponents form an arithmetic progression (2^0, 2^1, 2^2, 2^3, and so on); and the corresponding weighing values form a geometric progression (1, 2, 4, 8, and so on). If the individual, weighing value-digit products are summed for each digit position, the value of the corresponding decimal number is obtained. As an example, consider the binary number 0101. From right to left, the powers of two represented are 0, 1, 2, and 3 (2^0, 2^1, 2^2, and 23). The weighing values are 8, 2, 4, and 8 and the weighing value-digit products are 1, 0, 4 and 0. The sum of these products is the decimal number 5. A summary of the steps is shown below.

$$
\begin{aligned}
1 \times 2^0 &= 1 \times 1 = 1\\
0 \times 2^1 &= 0 \times 2 = 0\\
1 \times 2^2 &= 1 \times 4 = 4\\
0 \times 2^3 &= 0 \times 8 = \underline{0}\\
& \qquad\qquad\;\; 5
\end{aligned}
$$

5.9.1.9 Natural binary system. The natural binary system is the purest form of binary progression and the easiest to use and understand. The conventional decimal system is based on powers of 10. The number 9425.6 actually means:

$$9 \times 10^3 + 4 \times 10^2 + 2 \times 10^1 + 5 \times 10^0 + 6 \times 10^{-1}$$

In the natural binary system, place values are based on the powers of two so that the binary number 101101 means:

$$1 \times 2^5 + 0 \times 2^4 + 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 = 45$$

A comparison of the natural binary code to the decimal system with the code limited to four digit positions, plus the transition to the fifth position and the corresponding decimal numbers, is shown in Table XXI. Note that the natural binary code has no unused digit combinations and that no combination is repeated. However, the code does require more than one digit to change in going from one decimal digit to the next, as in the 7-to-8 transition.

5.9.1.10 Addition of natural binary numbers. Addition of two numbers in the natural binary code may be performed directly without translation to the decimal system. The rules are as follows and as indicated in the sample below:

a. If both digits are 0, write a 0 in the sum.

b. If both digits are different, write a 1 in the sum.

c. If both digits are 1, write a 0 in the sum and carry a 1 to the next column.

Addition:	Natural Binary	Decimal System
	1010	10
	+0101	+ 5
	1111	15

Check: Binary 1111 =

$(1X2^0) + (1X2^1) + (1X2^2) + (1X2^3) =$

$(1X1) + (1X2) + (1X4) + (1x8) =$

$1 + 2 + 4 + 8 = \underline{15}$

5.9.1.11 Subtraction of natural binary numbers. subtraction of two numbers in the natural binary code, like addition, may be performed without conversion. The rules and samples are given below:

Rules: A - B = D

a. 0 - 0 =

b. 0 - 1 = 1 (borrow 1)

c. 1 - 0 = 1

d. 1 - 1 = 0

Samples:

Natural Binary	Decimal System
1010	10
-0101	- 5
0101	5

Check: Binary 0101 =

$(1X2^0) + (0X2^1) + (1X2^2) + (0X2^3) =$

$(1X1) + (0X2) + (1X4) + (0X8) =$

$1 + 0 + 4 + 0 = \underline{5}$

5.9.1.12 Multiplication of natural binary numbers. the rules and sample of multiplication of natural binary numbers are shown below:

Rules: A x B = P

a. 0 x 0 = 0

b. 0 x 1 = 0

c. 1 x 0 = 0

d. 1 x 1 = 1

Samples: Natural Binary Decimal System

```
       1010          10
      x0101         x 5
       1010          50
      0000
     1010
    0000
   0110010
```

Check: Binary 0110010 =

$(0x2^0) + (1x2^1) + (0x2^2) + (0x2^3) + (1x2^4) + (1x2^5) + (0x2^6) =$

$(0x1) + (1x2) + (0x4) + (0x8) + (1x16) + (1x32) + (0x64) =$

$0 + 2 + 0 + 0 + 16 + 32 + 0 = \underline{50}$

5.9.1.13 Division of natural binary numbers. The rules and samples of the division process using natural binary numbers are shown below.

Rules: A + B = Q

a. 0 ÷ 0 = Undefine

b. 0 ÷ 1 = 0

c. 1 ÷ 0 = Infinity

d. 1 ÷ 1 = 1

Samples: Natural Binary Decimal System

```
     0010           2
  101/1010       5/10
```

Check: Binary 0010 =

$(0x2^0) + (1x2^1) + (0x2^3) + (0x2^4) =$

$(0x1) + (1x2) + (0x4) + (0x8) =$

$0 + 2 + 0 + 0 = \underline{2}$

5.9.2 Coding techniques. A primary decision in the selection or design of an encoder is the coding method to be used. The code is implemented by the pattern of segments on the face of the encoder disc and is dictated in large part by the application which, in turn, will determine the category of encoder to be used. Currently, almost all encoders are of two categories: incremental encoders and absolute (direct reading) encoders.

a. Incremental encoders are designed and constructed so that the pattern on the rotating disc forms a series of uniform marks or opaque lines, each precisely positioned. The output of the encoder is theoretically a series of identical square waves. Each pulse represents a small fraction of a revolution of the shaft being monitored. Some form of digital counter stores the number of counts. The data describes total angle or rotation experienced with reference to an arbitrary starting point.

b. Absolute or direct reading encoders have a disc pattern consisting of a series of concentric tracks, each containing a simple multiple of the other. Each position of the encoder defines an angular position in some digital code. The output of the instrument will remain accurate if turned off and then reenergized at any time in the future. It requires no auxiliary storage device.

With either incremental or absolute encoders, the digital code is based on a special number system with arithmetic and logic characteristics best suited to the application. In recent years with the advent of third generation digital computers, gigantic telemetering systems, and the growing use of automation, many number systems and coding techniques have arisen. To satisfy each individual requirement, varied codes are available which permit easy interface with existing systems without demanding elaborate translation or control circuits. Codes used in shaft position encoders can meet requirements ranging from digitizing a shaft position for decimal visual display to indicating antenna positions for tracking and control of space vehicles.

5.9.2.1 Incremental code. The incremental code shown in Table XXII is a regularly weighted code limited to two-digit positions. Consequently, it is symmetrical around the 3-to-4 transition since no other combination of digits is permitted. The usefulness of the incremental code is not immediately apparent since any two decimal digits separated by three intermediate decimal digits are represented by the same binary number (0 and 4, 3 and 7, and so on) . However, it has the advantage of counter reset, allowing the zero reference point to be any arbitrary shaft position. The incremental code can be used with up–down counters to accumulate a number representing shaft position. This code has the advantage that the counter can be reset to zero and thereby shift the zero reference point to any arbitrary shaft position. It has the disadvantage of being sensitive to noise and power failure and requiring some additional electronics (up-down detector and counter). An incremental track is often combined with an absolute encoder to indicate velocity (count over fixed-time interval) or to detect peaks and valleys.

5.9.2.2 Single contact encoders. A variation of the incremental encoder is the single contact encoder. The single contact encoder uses a two-layer circuit board. The surface of the top layer consists of a series of segments (one for each count). Each segment on the top layer connects to a single conductor of the 18 concentric conductors on the second layer. The 18 conductors are used for 1,000 counts and are connected to set-reset registers, which in turn operate translating circuits. A single rotating contact assembly connects power to the segment that corresponds to the angular position. The sequential signals are stored and translated. In the event of power interruption or for initial turn-on, a rotation up to a maximum of 20 counts may be required to reset the register. The encoder must generate a unit distance code, such as Gray code or cyclic decimal, in the storage register which then is translated to the desired binary code or decimal. This circuit has an advantage in providing lower torque and inertia than multiple contact encoders. Its disadvantages are:

a. Number of output lines required.

b. Number of turns required to generate a correct output.

c. Number of external circuits required.

5.9.3 <u>Binary decimal system.</u> A binary decimal number is one in which each decimal digit is represented by a set of natural binary bits or a binary word. For example, the number 227 can be written as the binary decimal number 0010 0010 0111.

5.9.3.1 <u>Binary coded decimals.</u> The binary coded decimal (BCD) is a method of coding decimal numbers in which a group of binary digits is used to represent each decimal digit. The group is called a “word” and each individual binary digit is called a bit (contraction of Binary digit). A group of four binary digits representing a decimal digit (or any other quantity defined by the group) is called a four-bit word. The BCD can be coded in any binary code, the most common regularly weighted code being the natural BCD (8-4-2-1 BCD).

5.9.3.2 <u>BCD background.</u> Some system applications require the display of output data to be monitored and used by operating personnel. In such cases, a primary performance requirement is conversion of output data to a form that can be rapidly and accurately understood by human operators. A common coding method used to satisfy this need is the BCD. Using BCD, the familiarity of Arabic decimal numbers can be combined with the useful properties of the binary system. This approach is used as an efficient compromise to derive maximum benefit from both machine and human capability. Although some loss in compactness and some added complexity in the arithmetic circuits are required, BCD numbers are easy to manipulate since they are similar to decimals.

5.9.3.3 <u>BCD implementation.</u> The BCD code is similar to the natural binary code except that each decimal decade is represented by a four-bit binary word. These bits can be weighed in various ways. The two most popular being the 8-4-2-1 (natural binary) and 4-2-2-1 (cyclic) codes. Figure 102 illustrates the 8-4-2-1 BCD code.

5.9.3.4 <u>8-4-2-1 BCD's.</u> The 8-4-2-1 BCD is a binary code in which only 10 digits of the decimal system are coded. Each decimal digit is represented by four binary digits (bits). Any decimal number is expressed by groups of bits, the number of which is equal to the quantity of digits in the decimal number. The BCD output is desirable when external decimal-to-binary and binary-to-decimal conversions are to be held to a minimum. With 8-4-2-1 BCD encoder output, only 10 conversion circuits are required for decimal display from computers, one for each decimal digit. The 8-4-2-1 BCD code is shown in Table XXIII. Note that six possible digit combinations are wasted.

5.9.3.5 <u>Bnary coded octal.</u> The binary coded octal system shown in Table XXIV is a BCD in which the first eight digits of the decimal system are coded. Each decimal is represented by three bits. Any decimal number is expressed by three-bit words, one for each decimal digit. The chief advantages of this system are the ease with which a mental conversion from octal to decimal can be made, the reduction in electronics in that only three bits are required, and no unused combinations exist.

5.9.3.6 <u>7-4-2-1 BCD's.</u> The 7-4-2-1 BCD is a system similar to the 8-4-2-1 BCD and is shown in Table XXV. The 7-4-2-1 code is a power saving code that requires only two "on" or "one" conditions to represent any decimal digit. Encoder usage of this code is limited, and it is shown here to illustrate the diverse number of BCD codes that exist.

5.9.3.7 <u>Two-out-of-seven binary codes.</u> The two-out-of-seven binary codes are a series of regularly weighted codes which have in common seven-bit words. As many excess binary digits are available, they are useful in error checking. A sample of two-out-of-seven codes is described in 5.9.3.8.

5.9.3.8 <u>Biquinary coded decimals.</u> The biquinary coded decimal is a BCD code utilizing seven-bit words to represent the decimal digits. The code is regularly weighted with values of O, 5, 4, 3, 2, 1 and is shown in Table XXVI. Since each coded decimal contains exactly two 1's, errors may be easily detected by simple comparison circuits in the external electronics. Variations exist in biquinary codes. One such deviation is the regularly weighted (8-6-4-2-0) odd-even biquinary coded decimal which has only six bits per word, or the biquinary code which only differs in digit designation. These codes are also shown in Table XXVI.

5.9.3.9 <u>Two-out-of-five binary codes.</u> The two-out-of-five binary codes are a group of codes that are similar to the two-out-of-seven codes except that five-bit words are used. Again, the error checking potential of the code is based on having an even number of 1's for any decimal representation. A two-out-of-five code is shown in Table XXVII for reference. The weighted values for this particular code are 7, 4, 2, 1, 0, with zero being a parity check bit.

5.9.4 <u>Nonweighted binary codes.</u> Nonweighted binary codes, as discussed previously, have no weight assigned to the various digit positions. The particular binary digit sequence assigned to any given code in this group, then, is assigned to serve a special purpose. These purposes are discussed in the following paragraphs and may be classified as follows:

a. Cyclic codes - reflected or nonreflected.

b. Noncyclic codes - reflected or nonreflected.

c. Combination codes - variations of any combination of codes and code characteristics.

Table XXVIII presents the notation and progression for five common binary systems and their decimal equivalent.

5.9.4.1 Cyclic codes. Cyclic codes are a group of nonweighted codes which possess the property of requiring only one bit to change when going from one digit to either adjacent digit (monostrophic or unit-distance code). For the decimal system, a cyclic code can be formed by changing the numbering system to count in cyclic decimal as follows: 1, 2, 3, 4, 5, 6, 7, 8, 9, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, and so on. The two digit change between 9 and 10 is thereby avoided. Binary cyclic codes are formed by assignment of the bits in a monostrophic manner. Cyclic codes can be reflected or nonreflected. In general, reflected codes utilize a pattern to form the code such that the same binary word or group of bits, less the MSD, represents two decimal numbers numerically equidistant from a reflection point. Numbers above and below the reflection point are differentiated by the MSD. Nonreflected codes have no such pattern.

5.9.4.2 Cyclic binary or gray code. The cyclic binary code is derived by considering the corresponding natural binary numbers and applying the following rule: Proceeding from left to right, copy the natural binary number except complement any digit immediately preceded by a “l” in the natural binary number. For example, the natural binary number 1010 can be transformed to the cyclic binary number 1111 by applying the above rule. Note that in Table XXVII there is only a one bit change between any two successive decimal representations. The Gray code is a typical reflected cyclic code of major importance and is shown in Table XXIX. Note that the Gray code is, less the MSD, symmetrical around the seven-eight transition and that only one digit must change in going from any given decimal number to the succeeding number. The Gray code is reflected and is monostrophic. The code, although only shown for 15 decimal digits, can be expanded as required. For special applications, the properties of the Gray code are used in combination with codes such as the Excess-3 BCD. In these cases, the resulting codes are no longer reflected. Refer to combination codes for further information.

5.9.4.3 Gray code - implementation. Although Gray code is a binary notation system, it must be decoded to derive its natural binary equivalent for most applications. This is usually a function of the interface circuits between the encoder and the parent system or a task performed by the output function of the encoder. However, a clearer understanding of the details of

Gray coding may be gained from the details of the decoding process. The rule for converting Gray code notation to its natural binary equivalent is that the most significant 1 (the 1 bit with the highest decimal equivalent) remains unchanged and each successive digit becomes complemented (a 1 becomes a 0 and a 0 becomes a 1) for as many times as there are 1's preceding it in the Gray code word. Referring to Figure 103 and observing the transition to the decimal value 21, we find the notation would be 11111. Using the basic rule, the decoding process would be as follows:

a. The most significant bit, with a weight of 2^4, or 16, 1 is 1 and remains unchanged. = 16

b. The next digit, with a weight of 8, is a 1 and is complemented once and becomes a 0. = 0

c. The next digit, with a weight of 4, is a 1 and is complemented twice, becoming a 1. = 4

d. The next digit, with a weight of 2, is a 1 and is complemented three times, becoming a 0. = 0

e. The last digit, with a weight of 1, is a 1 and is complemented four times, becoming a 1. = 1

f. Adding the weights of these bits = 21

Therefore, the decimal equivalent of the Gray code word 11111 is 21 and the binary equivalent is 10101. Due to the difficulty and accuracy limits in the mechanical alignment of sensor contacts, encoders using natural binary code can produce ambiguous outputs at the point of transition between two coded values. Various methods to overcome this fault have been developed, and one of the earliest was the use of the cyclic binary or Gray code (named after its inventor). The pattern arrangement for Gray code (see Figure 103) ensures that only one bit changes state for each progression as shown in Figure 104. Thus, a single row of sensors, positioned to within one digit of accuracy, will produce an output with a maximum error limited to one bit. Since the inherent error in any encoder is one bit, the overall accuracy of the encoder system remains essentially the same. This inherent error occurs because the detecting sensors cannot discriminate between the start and the end of a given segment on the encoder disc.

5.9.4.4 Gray code - design characteristics. Gray code has the advantage of being monostrophic; that is, a unit distance code since adjacent numbers appear on adjacent squares (such as at unit distance) on a Vietch diagram. Therefore, Gray code requires only a single bit to change when passing from any number to the adjacent number. This feature simplifies the encoder code pattern and thereby reduces the cost of the encoder. Gray code is easily translated to natural binary numbers by the following rules:

a. The most significant natural binary bit is identical to the most significant Gray bit.

b. If the n^{th} natural binary bit is 0, the (n-1)th natural bit is identical to the $(n-1)^{th}$ Gray bit.

c. If the n^{th} natural binary bit is 1, the $(n-1)^{th}$ natural bit is the opposite of the $(n-1)^{th}$ Gray bit.

In Boolean terms, conversion of Gray code to a natural binary equivalent is an "exclusive OR" gate function expressed as:

$$B_{n-1} = G_{n-1} \cdot \overline{B_n} + \overline{G_{n-1}} \cdot B_n$$

The $(n-1)^{th}$ binary bit is True (logical “1”) if the $(n-1)^{th}$ Gray bit is True (logical “1”) and the n^{th} binary bit is False (logical “0”), or if the $(n-1)^{th}$ binary bit is True.

5.9.5 Cyclic decimal code.

5.9.5.1 Cyclic decimal - background. Another technique, developed to overcome the basic problem of output ambiguity, is the modification of the standard Arabic decimal system to a cyclic decimal progression as shown on Figure 105. Cyclic decimal is similar to Gray code in that only a single bit is changed in progressing from any number to the adjacent value. This technique provides a code that requires only one switching change between adjacent numbers. The Arabic number system, modified to the cyclic decimal system can then be expressed in a binary form with a group of four binary units representing each decimal integer. This code can be conveniently translated from cyclic to Arabic decimal form as part of the encoder output function. The operations internal to the encoder can be performed in a non-ambiguous binary code and an output provided in a standard Arabic decimal format, either most significant or least significant digit first as determined by overall system demands.

5.9.5.2 Cyclic decimal - implementation. The rules for translating from Arabic decimal to cyclic decimal are as follows:

a. An Arabic decimal digit that follows an even Arabic digit is not changed.

b. An Arabic decimal digit that follows an odd Arabic digit is changed to the nine’s complement when expressed in cyclic decimal.

c. The most significant digit of any number is not changed since it is understood to follow a zero.

The rules for translating from cyclic decimal to Arabic decimal are similar. The odd or even digit used to determine the nine’s complement requirement is always taken from the next more significant Arabic digit. In the binary coding process (see Figure 105), each of the cyclic decimal numbers is represented in the form of a 4-bit binary word. The four bits (A, B, C and D) have no numerical weight or numerical value. The basic code counts only to decimal 10 by using discrete combinations of the four bits, as shown on Figure 105. The cyclic decimal code has the general advantage characteristic of monostrophic (unit distance) codes including high resolution, simplicity, and mechanical efficiency due to lower reflected inertia. However, this approach has the disadvantage of requiring that all detection sensors make and break the full value of voltage and current required by the load, which has an adverse effect upon encoder service life and reliability.

5.9.5.3 Cyclic bnary decimal. The cyclic binary decimal system is a combination of cyclic binary and binary decimal concepts. Each decimal digit is represented by a set of cyclic binary bits or a cyclic binary word. These systems can be used separately or in combination as the cyclic binary decimal.

5.9.5.4 Coding. Coding is the process of selecting the best number system for a given application and implementing the selected system in the form of a patterned encoder disc. As the disc rotates in response to an input shaft variable, the shaft position is represented by the relative position of the segments of the disc. The code determines the form of the encoder output.

5.9.5.4.1 Natural binary. A pattern representing a typical 5-bit natural code is shown on Figure 106. The topmost track, called the Least Significant, has a weight of 1 or 0 representing 2°. The second track has a weight of 2 or 0 representing 2^1. The third has a weight of 4 or 0 representing 2^2. The fourth track has a weight of 8 or O representing 2^3, and so on. By examining this pattern, it can readily be seen that if a line of sensors were placed vertically across this pattern and the correct weights were assigned to each track, it is then possible to derive the decimal equivalent of the binary number by adding the tracks. The sum of these numbers would be the decimal number represented by the binary word. Referring to Figure 106, if a line of contacts were placed across the pattern representing the binary word 10101, conduction would occur on contacts 1, 4 and 16. The sum of these numbers would be the decimal number 21 which is the equivalent of that binary word.

5.9.5.4.2 Gray or cyclic binary. Other basic number systems are similarly coded. Another example of an elementary disc pattern is shown on Figure 103 which depicts a typical 5-bit Gray code or Cyclic Binary implementation. The pattern arrangement is the same regardless of the detection technique. For a contact encoder, the dark areas of the patterns shown on Figures 106 and 103 would be conductive while the light areas would be insulating material. In an optical system the pattern would consist of transparent and opaque areas, and in a magnetic encoder disc the dark areas would be segments of magnetized ferritic material. The selected number system is coded onto the disc in accordance with the desired detection scheme.

5.9.5.4.3 <u>BCD.</u> The first 10 binary numbers are used to represent the 10 Arabic number symbols. Each decimal integer or decade is represented by a group of four binary units and each decade is considered separately. The units, tens, hundreds, thousands, and so on of the decimal number are each represented by a separate group of four bits. Table XXVIII lists the natural BCD equivalent of the decimal values from 0 to 17.

5.9.5.4.4 <u>Cyclic BCD.</u> Because of ambiguity problems inherent in implementing any code based on natural binary numbers, a cyclic BCD or cyclic decimal code also has been developed. This code employs the same basic approach as natural BCD coding except that the individual binary units in each group of 4 bits are weighted 4-2-2-1 as shown on Figure 107. The same rules for decoding apply as used for Gray code; however, one additional step is required to derive a decimal equivalent. Using the decimal value 21 as an example, Figure 107 shows the cyclic BCD equivalent as the binary words 0011 and 0001. Converting from Gray code yields the binary words 0010 and 0001 which, in turn, is the same as the natural BCD notation.

5.9.5.5 <u>Nonreflected cyclic codes.</u> Nonreflected cyclic codes are also useful for encoder applications and usually originated to solve specific problems. Assignment of logical "1's" and "0's" is usually at random. To illustrate such a code (29 x 10^9 possible combinations), consider a solution to the following design criteria:

A binary code for a 10-digit system which

a. allows the nine's complement to be formed with a one-digit change,

b. in the last bit, minimizes power supply requirements by limiting the number of "On" circuits to three per decimal digit for any number in the code (1111 is forbidden),

c. restricts the use of 0000 so that power failure can be detected, and

d. is munostrophic.

One code using BCD's and a cyclic decimal system is shown in Table XXX. The code is used successfully in encoders.

5.9.6 <u>Noncyclic codes - nonreflected codes.</u>

5.9.6.1 <u>Excess-3 code.</u> The Excess-3 is a nonreflected code of major importance due to the fact that it is self-complementing. The Excess-3 code is shown in Table XXXI with the method of derivation. As shown in the table, the Excess-3 code is formed by selecting the 8-4-2-1 binary coded decimal equivalents of decimal numbers 3 through 12, leaving the first 3 digits of the 8-4-2-1 code in excess (not used). Note that if the bits of any Excess-3 number are inverted (1's for 0's and 0's for 1's), this number also appears in the code. If the process is continued for digits zero through four, it becomes apparent that the code is a mirror image about the four-five transition. Also, note that if the digits of an Excess-3 number and its inversion are summed, the result is always equal to nine. The Excess-3 code is self-complementing, making a subtraction problem possible by addition using the nine's complement method without computer memory programming of the complements. Forbidden words of the code are excellent for error checking, but translation to decimal requires a subtracter computer circuit.

5.9.6.1.1 Example. The Excess-3 decimal code is illustrated on Figure 108. This code has several advantages where direct input to a computer is desired. Excess-3 decimal code is similar to the 8-4-2-1 BCD code except that the number has three added to it; that is, the digit O is represented by 3, 1 by 4, 2 by 5, and so on. This code produces a well-balanced pattern with the added feature of being a natural nine's complement pattern. Thus, 9 (1100) is the complement of 0 (0011), 1 (0100) is the complement of 8 (1011), 2 is the complement of 7, 3 of 6, and 4 of 5. This feature is useful where a plus or minus count is desired. For a plus number, the natural number is used; for a minus number, the numbers from 9 are complemented, producing a decreasing count from the same disc or pattern.

5.9.6.1.2 Excess-3 natural binary. The Excess-3 code shown in Table XXVIII is the same as natural binary except that it has been displaced downward three places, making the actual natural binary representation for 3 correspond to 0. The numbers 0 to 9 are complementary; for example, 0 replaces 1 and 1 replaces 0. The same is true for 2 and 7, 3 and 6, 4 and 5. Subtraction of any number from 9 is, therefore, the same as the pure binary representation of that number except that the 0's and 1's are interchanged.

5.9.6.2 Excess-3 BCD. The Excess-3 BCD is a combination of the Excess-3 code and BCD techniques previously described. The code is shown in Table XXXI along with the Excess-3 code.

5.9.7 Combination codes. Combination codes are formed by using two or more existing codes, each having desirable characteristics or meeting specific needs. Two examples are given in the following text.

5.9.7.1 ICAO code. The ICAO altitude reporting code (formerly MOA-Gillham code) is a combination code designed for automatic reporting of aircraft altitude. The code is designed to report in either 500- or 100-foot increments to meet both European and United States standards. The ICAO code is a combination of a reflected cyclic code (Gray) and a nonreflected cyclic code that allows altitude reporting from -1,200 feet to 127,000 feet. The encoder design may be either single- or multi-turn; the multi-turn being shown in Table XXXII by a particular commutator code bit arrangement. The 500-foot increments are in Gray code spaced symmetrically around 500-foot aircraft altitudes. A decoded Gray of 3 (left-hand column) indicates a nominal aircraft altitude of 500 feet, actually between 250 and 750 feet if both the code increment and code transition points are included. (This particular accuracy is sufficient in many cases as aircraft fly east-west paths on specific 1,000-foot bands and north-south on others.) The 100-foot increments required by airport traffic controllers are identified by a three-bit nonreflected cyclic code. The code is derived such that any 100-foot increment retains the same bit configuration (C1, C2 and C4) when occurring at a Gray code transition, and thus is based on the odd-even characteristics of the decoded Gray code. This is shown in the table for altitudes of 250 ft, 750 ft, 1,250 ft, 1,750 ft, and so on. The ICAO code is entirely monostrophic in that no more than one bit is ever required to change for any altitude increment. A two-bit change is then a forbidden occurrence, indicating an encoder or transponder error to the aircraft traffic controller. Table XXXIII indicates the forbidden bit changes for the 100-foot code. The entire code through 127,000 feet with a typical commutator (disc) design is shown on Figure 109.

5.9.7.2 <u>ICAO code - background.</u> The ICAO code was developed by the British Air Ministry for the reporting of altitudes in automatic flight control. When first developed, it contained eight bits of Gray code representing 256 increments of 500-feet for a total of 128,000 feet. The 500-foot increment was not small enough for use in the continental United States, and these increments were further divided into 100-foot increments. More bits were added to the code, thereby modifying it. It was then adopted by the International Civil Aviation Organization (ICAO). This code is of particular interest because of the new programs for automatic altitude reporting, and because it is a prime example of a class of useful, special purpose, ambiguous coding. ICAO code features the combined use of cyclic decimal coding for the least significant decimal character and Gray code for the higher order bits. The details of the progression and pattern for the ICAO code are not standard throughout the encoder industry, although a standardized altitude transmission code is produced as an output. Generally, the variations among manufacturers occur in the means of encoding the least significant bits (100-foot altitude increments). Some ICAO encoders use a four-bit code for the 100-foot data while others accomplish the same encoding task with a three-bit word. Both approaches are discussed below.

5.9.7.3 <u>ICAO code - implementation.</u> The progression and pattern for ICAO code implementation using Gray code and a four-bit cyclic decimal word are shown on Figure 110. The altitude unit’s and ten’s decades are assumed to be zero and are not included in the disc pattern. The least significant bits represent the hundred’s decade, and four bits (A, B, C, and D) of a standard cyclic decimal code are used to code this value. The odd or even decimal configuration of the Gray coded most significant decades (500-foot altitude increments) determines the hundred’s decade output count. If the Gray code count is odd, the D bit of the cyclic decimal code is complemented. Inversely, if the Gray code count is an even decimal value, the D bit is not complemented. This complementing operation decodes the cyclic decimal output to an equivalent Arabic decimal code. The Gray coded words are incremented by 1 for every 1,000 feet of altitude increase requiring external logic and arithmetic translation circuits to perform the following operations:

a. Determine the odd or even configuration of the Gray code output and translate Gray code to decimal notation.

b. Translate the cyclic decimal output to Arabic code. If Gray code is odd, complement the D bit of encoder output; if Gray code is even, do not complement the D bit of the encoder output.

c. Translate the Arabic code to decimal and multiply by 100.

d. Multiply the decimal value of the Gray code count by 1000.

e. Add the 100's to the 1000's.

f. Subtract 1,200 from the sum to obtain the altitude in feet. The ICAO code is offset by 1,200 feet from the zero position to permit effective outputs from -1,200 feet to 127,000 feet, typically.

To apply these rules to a typical situation, suppose an altitude of 1,500 feet were to be transmitted. The Gray code output would be 11000 and the cyclic decimal output would be 0101. As shown on Figure 104, the Gray code output would be 2, an even integer. The D bit of the cyclic decimal output is, therefore, not complemented and would translate to an Arabic decimal value of 7 (see Figure 105). Multiplying 2, the most significant value, by 1,000, and 7, the least significant value, by 100, and adding the products would yield:

$$(2 \times 1{,}000) + (7 \times 100) = 2{,}000 + 700 = 2{,}700$$

Then, subtracting 1,200 from this sum:

$$2{,}700 - 1{,}200 = 1{,}500$$

The decoding process would be similar for other altitude values as shown on Figure 110. Another typical implementation of ICAO or Gillham code using a three-bit cyclic decimal word for the least significant value is shown on Figure 111. As in the previous four-bit example, the code has no particular weighting of bits and is decoded by bit position as shown on Figure 112. The 100-foot increment table is used on Figure 112 in conjunction with the associated Gray code word. If the 1's in the Gray code word are odd, the odd column of the table is used and if even, the even column is used.

5.9.8 Gray coded Excess-3 BCD. The Gray coded Excess-3 BCD is a combination code derived from the Excess-3 BCD and Gray codes. The combination retains the properties of both codes which are indicated below.

Property	Code Origin
Easily formed nine's complement (one-bit inversion)	Excess-3 BCD
Plus-minus operation with multi-turn encoders by complementation in the minus range	Excess-3 BCD
Cyclic or monostrophic	Gray
Easy translation to natural binary	Gray
Easy manipulation (familiarity with decimals)	Excess-3 BCD
High count density possible	Gray

The code is formed by adding 3 to the particular Arabic digit and encoding this result in Gray BCD code. For example, to encode the Arabic decimal 2, add 3, and encode in Gray.

2 + 3 = 5

5 = 0111 (Gray-coded Excess-3 BCD)

The code is shown in Table XXXIV. Note the transition between 9 and 10 or 19 and 20.

5.9.9 Two-out-of-five codes.

5.9.9.1 Two-out-of-five codes - backmound. Two-out-of-five, or biquinary codes, provide a useful technique for applications requiring display of decimal information, especially if a parity check is desirable. This code can be used with such devices as typewriters, adding machines, or visual indicators which require a direct decimal input. If the encoder output is only required to operate peripheral equipment and the output does not need to be stored or transmitted, it is often more efficient to generate the required decimal signals directly from the encoder, thus eliminating the need for intermediate interface circuits. There are a number of variations on the basic biquinary code which can be combined with processing circuits to provide decimal signals in a directly usable form.

5.9.9.2 Two-out-of-five codes - implementation. The two-out-of-five code derives its name from the fact that a five-bit binary word is used to represent each of the 10 basic Arabic decimal numbers (0 through 9). As shown on Figure 113 and Table XXXV, two-out-of-five bits in each word are always 1's and the remaining bits are always 0's. Except for the decimal value zero, the first four bits are weighted 1, 2, 4, 7 and the fifth bit is used to provide even parity. Where direct decimal outputs are required, a separate output line must be provided for each of the 10 Arabic numerals. This means that 10 lines are required for each decimal digit; for example, a three-place output would be carried on 30 output lines. Direct decimal output adds complexity to the encoder design. A compromise, almost as useful in operating decimal output devices, is the odd/even biquinary code shown on Figure 114. This code consists of the standard five biquinary coded bits plus an odd/even selector bit. The selector bit denotes the odd or even configuration of the output count. This technique reduces the number of output lines required for direct decimal readout from 10 to 6. Figure 115 is a typical odd/even biquinary output circuit; the odd/even bus selector connects the odd bus to ground for odd numbers and connects the even bus to ground for even numbers.

5.9.10 Special purpose codes.

5.9.10.1 Special purpose codes - background. For various special purpose applications, unique number systems have been developed to derive unit distance codes, codes that can be easily complemented, or codes that produce plus-minus outputs. Three such applications are time and angle encoders, multispeed encoders with plus-minus spans, and center-zero single-turn encoders. These situations are typical of the design problems which must be solved to make effective use of encoders in modern systems.

5.9.10.2 Special purpose codes - implementation time and angle. Time (hours, minutes and seconds) or angle (degrees, minutes and seconds) employ special number systems that require special codes either to obtain a unit distance code or to obtain a code that is easily complemented. A unit distance code for the ten's digit of minutes (0-5) or seconds (0-5) that can be complemented by inverting a single bit is shown in Table XXXVI. In general, an easily complemented unit distance code for any even-numbered span can be formed by the following rules:

a. Subtract the span from the next higher integral power of 2.

b. Divide this difference by 2 and add the result to the original group of numbers.

c. Encode the new group in Gray code.

For example, to obtain a unit distance code for 0 to 23 hours that may be complemented by inverting a single bit, subtract 24 from 34 (which is 2^5) and add half the difference (4) to the original numbers. Table XXXVII details a time and angle code based on the above principle.

5.9.10.3 Plus-minus spans with multispeed encoders. To obtain plus-minus number systems, it is convenient to use a code which is easily complemented to obtain negative numbers. One difficulty with this technique is that the complementing operation produces two zero positions, +000 and -000. This occurs since the complement of 999 is 000. Double zeros result in an additional error of 0.5 quantum. To avoid the double zero, it is necessary to use twice as many tracks and contacts on the high-speed discs and to switch from one set of contacts to the other at zero. This type of construction puts no restriction on the number system or coding used, although it is relatively expensive.

5.9.10.4 Center-zero single turn encoders. A similar problem arises with single-turn encoders which use a unit distance code such as Gray code, and require a plus-minus output. If the error due to a double width zero cannot be accepted, a special pattern can be made. This pattern has both +000 and -000, but each sector is only 0.5 normal quanta in width (angular travel) so that no error is added because of the plus-minus number system.

5.9.11 Code selection criteria.

5.9.11.1 BCD versus binary. Use of BCD versus binary is usually determined by system considerations. However, for encoder use BCD has 30 percent more contacts and torque and is slightly larger and more expensive. The 30 percent redundancy can be used for error detection (sense for unused codes).

5.9.11.2 Monostrophic versus weighted codes. Monostrophic encoders have fewer contacts, require no diodes for the first disc, and are generally smaller and less expensive than encoders employing the more familiar weighted binary of BCD codes. They have minimum torque and inertia. They are easier to use if long cables are necessary and have the simplest storage circuits. However, encoders with weighted binary or BCD codes should be considered in control systems using comparators or systems employing arithmetic circuits or where it is necessary for the encoder to drive heavy loads (more than 5 milliamperes or 30 volts). When the system rewires the connection of one out of two or more encoders to a common data bus or storage register, the absence of diodes in single-turn cyclic decimal or Gray code encoders is no longer an advantage. Adding diodes for parallel operation may tip the scale in favor of weighted codes. Multi-turn Gray code or cyclic decimal encoders employ diode OR gates for all except the first high-speed disc. In this instance, there is less reason to change to weighted codes.

5.9.11.3 Direct decimal. Decimal or biquinary encoders have an advantage in simple systems where no storage, comparison, or arithmetic operations are required and where cable cost or size is not important. Typical applications are indicating or direct printout systems. Decimal encoders are usually much larger than BCD or biquinary encoders.

5.9.12 Encoder logic. The following paragraphs describe the logic equations, symbols, and diagrams used in encoder circuitry, Basic to encoder usage is the fact that output is in terms of logical 1’s and 0’s. Circuit design must discriminate between a one or zero for any given digit existing or not existing. The following digit requires this same determination, and the position summation of these individual digit values determine the value of encoder output. These digit relationships are best expressed using the conjunctive of Boolean algebra. The portion of Boolean algebra covered herein, then, is limited to the conjunctive relationships of deductive Aristolean logic as formulated by George Boole in 1847. This logic is the study of single-valued functions as represented by the words AND, OR, AND NOT (NAND), and OR NOT (NOR). A summary of the Boolean laws and functional operators (symbols) is shown in Table XXXVIII.

5.9.12.1 Logic functions. Consider a typical logic equation or functions such as:

$$a \cdot b = c \qquad \text{or} \qquad ab = c \qquad \text{or} \qquad ab \rightarrow c$$

(equivalent forms)

The equation is read "if a and if b, then c". The equation states two conditions which must be present in order to obtain a certain result. If a and b are present, c is implied. The equation can be presented pictorially as shown on Figure 116 by a series circuit. If, and only if, both switches A and B are closed can lamp C illuminate. The foregoing illustrates the AND function. If the AND function logic equation is inverted to the negative or NOT sense, the equation is still true. Inversion of the equation yields:

$$\bar{a} \cdot \bar{b} = \bar{c}$$

The equation is now read “if not a and not b, therefore not c”. By examining the diagram on Figure 116, the following equations are also true. The equations were already implied by the foregoing (if and only if).

(1) $a \cdot \bar{b} \rightarrow \bar{c}$ Read "if a and not b, then not c".

(2) $\bar{a} \cdot \bar{b} \rightarrow \bar{c}$ Read "if not a and not b, then not c".

All the above equations, although logically true by examination of the diagram, are actually derived from the Boolean rules of inference, two of which are shown in Table XXXVIII. Nineteen such rules, not necessarily independent, form a full complement of rules for inference. Note that the definition of the AND gate (Figure 116) allows the circuit to perform the four equations previously discussed. With a rearrangement of the pictorial circuit, the inclusive OR function can be expressed as shown on Figure 117. The inclusive OR function logic equation is:

$$a + b = c$$

The equation is read "if a or if b, then c". As shown on Figure 117, if switch A or if switch B is closed, then lamp C can illuminate. The exclusive OR logic equation is:

The equation is read "if a and not b, or if not a but b, then c." It means that c occurs if, and only if, either a or b, but not both, are present. The exclusive OR function is similar to a hall light in a house controlled from either upstairs or downstairs. When the upstairs switch is used to turn the light on, the downstairs switch will turn the light off. The exclusive OR circuit will translate parallel Gray code encoder output to natural binary code. Figure 118 illustrates this logic function.

5.9.12.2 Logic diagrams and truth tables. A truth table is a tabulation of all possible conditions for a given set of variables with a result that indicates the truth or falseness of that particular set of conditions. Consider the former example of the series circuit and the associated logic equation. All possible conditions for the two switches and the light are tabulated in Table XXXIX. A zero indicates an open switch, a non-illuminated lamp, or a False (impossible) result. A one indicates a closed switch, an illuminated lamp, or a True (possible) result. Note that the number of nonrepeating conditions is equal to 2^N, where N equals the number of variables. In this case 2^N is 2^3, or eight possible states of the three variables. From the result column, only four sets of True or possible states of the variables exist. If these results are summarized, the following logic equation can be written:

$$\begin{array}{ccccccccc} (1) & & (2) & & (3) & & (4) & & (5) \\ \overline{abc} & + & a\overline{bc} & + & \overline{a}b\overline{c} & + & abc & = & 1 \end{array}$$

The equation is read:

(1) not a and not b, then not c; or

(2) a and not b, then not c; or

(3) not a but b, then not c; or

(4) a and b, then c

(5) are all True

A logic diagram can be used to illustrate the equation possibilities and will represent the circuits required by a computer to perform the given operations. Such a diagram for the previous equations is shown on Figure 119. Referring to Figure 64, the AND blocks generate an output if, and only if, all inputs are present. The inclusive OR block generates an output if, and only if, an AND gate output or outputs is present. (All inputs are assumed to be of one polarity for this simplified discussion. Discussion of actual computer circuits is beyond the scope of this handbook.) Logic operations in a computer or encoder can use a variety of electronic components in the logic circuits. Logic circuits are named by the components used or feature of the process. The abbreviations appearing in encoder literature are listed below for reference.

Abbreviation	Description
RTL	Resistor-transistor logic
RCTL	Resistor-capacitor-transistor logic
DCTL	Direct-coupled transistor logic
DL	Diode logic
LLL	Low-level logic
CML	Current mode logic
DTL	Diode-transistor logic
TTL	Transistor-transistor logic

5.9.12.3 Encoder logic circuits - code translation. One of the uses of logic circuits with an encoder is code translation. The Gray to natural binary conversion is typical and is described below. The Gray code is processed in serial, MSD first, by exclusive OR logic according to the following rules:

a. The Gray MSD is identical to the binary MSD.

b. If the N^{th} natural binary bit is 0, the n-1 binary bit is identical to the n-1 Gray bit.

c. If the N^{th} natural binary bit is 1, the n-1 binary bit is the complement of the n-1 Gray bit.

Implied from the rules set forth, the following Boolean equations can be written, where B equals binary and G equals Gray.

a. $G^{MSD} = B^{MSD}$

b. $\bar{B}^{N} \cdot \bar{G}^{N-1} = \bar{B}^{N-1}$

$\bar{B}^{N} \cdot G^{N-1} = B^{N-1}$

c. $B^{N} \cdot G^{N-1} = \bar{B}^{N-1}$

$B^{N} \cdot B^{N-1} = B^{N-1}$

Step a requires no logic processing. Combining the equations for a True B^{N-1}, we obtain an operating equation for the code translation:

$$B^{N-1} = \bar{B}^{N} \cdot G^{N-1} + B^{N} \cdot \bar{G}^{N-1}$$

The equation is read “B to the N minus one is True (1) if B to the N is True (1) and G to the N minus one is True (1), or if B to the N is True (1) and G to the N minus one is False (0).” The logic diagram to obtain this equation for a five-bit Gray code is shown on Figure 120. The G^N digit is processed directly to the 2^N digit (1 or 0). If G^N is 0, the fourth exclusive OR gate receives no input. Conversely, if G^N is 1, the OR gate receives an input. Thus, the OR gate is set up to process the G^3 to 2^3 conversion. Now if G^N is 0 and G^3 is 1, the exclusive OR gate has a 1 output (by definition) and 2^3 appears in the binary count as a 1. If G^N is 1 and G^3 is 1, the gate has two inputs and no output. Therefore, 2^3 appears as a 0 in the output count. Similarly, G^3 sets up exclusive OR gate number 3 for the G^2 to 2^2 conversion.

5.9.12.4 Lead-lag sensor selection. Logic circuits are also used with an encoder to select the leading or lagging sensor to avoid ambiguity. The logic circuits for V-scan and M-scan must:

a. Select the lagging sensor (2_{lag}^N) for the 2^N track when the 2^{N-1} sensor reads 1, and

b. Select the leading sensor (2_{lead}^N) for the 2^N track when the 2^{N-1} sensor reads 0.

The equations for the operation using “lead” for the advance or leading sensor and “lag” for the retard or lagging sensor are:

$$\text{(A)} \quad 2^{N-1} \cdot 2_{lag}^N = 2^N$$

$$\text{(B)} \quad 2^{N-1} \cdot 2_{lead}^N = 2^N$$

Combining:

$$\overbrace{2^N = 2^{N-1} \cdot 2_{lag}^N}^{\text{Part A}} + \overbrace{2^{N-1} \cdot 2_{lead}^N}^{\text{Part B}}$$

which is read "2^N is True if 2 to the N minus 1 is True and 2 to the N lag is True, or if 2 to the N minus one is False and 2 to the N lead is True.” The equation is divided into two parts, A and B, either of which will produce a true 2^N.

5.9.12.4.1 Example of serial scan processing. A logic diagram to perform the equation is shown on Figure 121. The operational amplifier is used as an inverter and produces the complement of the input. Sequence for each part of the logic equation is shown on the diagram. Part A of the logic equation requires a True 2^{N-1} and a True 2_{lag}^N; and correspondingly, these inputs are labeled as a True A. The True A is applied to the operational amplifier and lower AND gate. The lower AND gate then has two True A inputs and supplies a True A output to the inclusive OR gate. The OR gate provides a True A output at 2^N. Part B of the equation requires a False 2^{N-1} and a True 2_{lead}^N to provide a True 2^N. The False B is applied to the operational amplifier where it is inverted and appears as a True B at the input to the top AND gate. The AND gate also receives a True B from the True 2_{lead}^{N}, and thus provides a True B to the inclusive OR gate. The OR gate then provides a True B at the 2^N output. The False 2^N appearing at the output of the right-hand operational amplifier for True 2^N is used for the 2^{N+1} sensor selection. In this example of self-contained logic, V-scan proceeds serially, MSD first. Parallel processing is also possible with a parallel-scan output matrix.

5.9.12.4.2 BCD encoders. For BCD encoders, a combination of V-scan and U-scan logic is used and provides digit outputs in serial form with parallel reading of the digit bits. The least significant four-bit digit is read first and digits time-share the logic circuit. Each individual digit has its own common track to allow parallel bit reading. Thus , a reading of 3599 is processed serially 9, 9, 5, 3 while the bits are read in parallel as 1001, 1001, 0101, 0011. Parallel word output is possible if the logic circuit for each digit is repeated. The logic diagram for one decade of serial word output is shown on Figure 122.

5.9.12.4.3 Multiple encoders. Where several encoders are used simultaneously, the economies of a single, time-shared parallel or serial scan matrix is used and each encoder is interrogated as desired. As shown on Figure 123, all encoder output leads are connected to a bus and the desired encoder energized by a computer signal that drives its common sensor lead. All encoder bits are gated through internal diodes to isolate the noninterrogated bit lines. If serial output is desired, a serial or parallel scan matrix is used. Parallel data output requires a parallel scan matrix. (A serial scan matrix receives inputs one at a time and produces outputs one bit at a time. A parallel scan matrix receives encoder bits simultaneously, but reads out in serial or parallel as desired.) A serial scan matrix is illustrated logically and functionally on Figures 124 and 125. A parallel scan matrix requires the additional components shown on Figure 126. In the serial matrix, all encoder bits are supplied to individual AND gates through isolation diodes where they await an externally furnished timing signal. The B^0 bit (LSD) is read first when the To pulse arrives at the LSD AND gate. The output of_the gate is furnished to inverting amplifiers which supply a B^0 and B^0 to a flip-flop. In combination with a clock input, the flip-flop holds the B^0 state in a static condition during the bit scan, supplies the logical “1” and “0” output to the readout equipment, and sets the AND gates for the higher order bits. In accordance with V-scan sensor selection logic, the next higher order AND gate is furnished with the True required signals (bit data, timing pulse, and_previous bit reading) for output. The selected AND gate for the bit (B^1 or B^1) provides an output to the associated OR gate which pulses the flip-flop through the inverters. Consequently, bit two of the readout is furnished to the computer and bit three AND gate is set. The process continues serially until B^N is furnished, completing the encoder readout cycle.

5.9.12.4.4 Parallel scan processing. In the parallel scan matrix, the AND gates perform the V-scan logic selection in accordance with flip-flop output, but do not require a sequential timing pulse as all bits are read simultaneously. When both bit and flip-flop output are present simultaneously, the selected AND gate provides an output via the OR gate to the following inverting amplifiers which generate bit and complement for the readout equipment. As in a serial scan matrix, the flip-flop stores (holds) the B^0 readout state until the bit scan is complete. Since one clock time is usually used to set the flip-flop, a total of two bit times is required for a single readout. In any case, the logic equations previously stated for V-scan sensor selection determine flip-flop operation.

5.9.12.5 Direction sensing logic. Direction sensing logic is to indicate the direction of shaft rotation. It usually requires additional sensors, disc tracks, or both. In incremental encoders, direction sensing may be accomplished by placing a second sensor on the LSB track located in quadrature (90 degrees) from the initial sensor. The differentiated output of the initial sensor occurring at the leading and trailing edge of the logical "1"-“0” transitions then bears a specific relationship to the normal output of the direction sensor. This relationship may be expressed by the following logic equations which differ as shaft rotation changes:

$$\text{Clockwise} = DA^1 \cdot B^0 + DA^0 \cdot B^1$$

$$\text{Counterclockwise} = DA^1 \cdot B^1 + DA^0 \cdot B^0$$

The relationship of these pulses is shown in Figure 127. A logic circuit to perform the required logic is shown in Figure 128.

5.9.12.6 Set-Reset logic. Set-Reset logic is used in an encoder to improve signal-to-noise ratio by reverting a readout to the previous reading if noise error exists. Encoder construction requires two LSB tracks and sensors, such that the sensors are alternately “On” and “Off”, but with overlap. Normally, the 2° track is defined as the Set track and 2° as the Reset track. Detection of the 2° state is made through latch techniques and is held until Reset. An associated selector circuit operates in accordance with the truth table shown in Table XL (for the Set-Reset definitions and track assignment discussed). As shown, the present output is independent of the previous value except when both Set and Reset are a logical “0”, in which case the present output equals the previous output. A basic logic circuit to perform the criteria set forth in the truth table is shown on Figure 129.

5.10 Applications, tradeoffs, and error.

5.10.1 Applications.

5.10.1.1 Applications - general. One of the most difficult decisions facing the system engineer is the design or selection of an encoder suited to detailed needs and requirements. Often the important system characteristics are determined and fixed far in advance of considering encoder hardware. If the system development progresses without early allowance for the encoding function, the system engineer may be faced with solving an encoding problem far beyond the complexity implied by the system function. This disproportionate complexity results from establishing too much of the system design before selecting encoder hardware or without at least considering it. In such cases, undue limitations may eventually have to be placed upon size, resolution, power consumption, weight, or any number of other critical encoder design factors. To avoid this problem, the encoding function must be considered early in the system design and development phase. Encoder requirements must be identified and defined, the possibilities investigated, and the available options analyzed to yield the best system solution. The following discussion presents encoder selection criteria and provides a general basis for evaluating requirements relative to specific encoder units.

5.10.1.2 Encoder classes. Encoders, regardless of the manner in which they perform the encoding function, can be classified as belonging to one of two major families of encoders: incremental or absolute. A first consideration will be to decide which family is best-suited to system needs.

5.10.1.2.1 Incremental encoders. The incremental encoder is by far the simplest since its only requirements are to generate a single signal for equal angular increments of shaft angle. The encoder may also contain a zero reference marker. The direction of shaft rotation can be readily detected through one additional code sensor. Circuitry is simple and power requirements modest. High resolutions in minimal size units are possible, particularly in the optical types.

5.10.1.2.1.1 Advantages vs disadvantages. There are advantages to such an encoder and weaknesses as well. If for any reason power is interrupted to the encoder or a transmission or reception failure occurs, counts will be lost . In the encoder without a zero marker, this loss is permanent and results in an error which will persist until the external counter is reset to zero. In units with zero reference, the error will persist until the reference has been sensed. In addition, some means must be provided for accumulating the output of the encoder. The required counter may be either external or internal. It should be noted that in systems using a number of encoders, time-sharing becomes impossible and every encoder must be equipped with its own counter. This leads to a considerable increase in cost, bulk, and lower reliability.

5.10.1.2.1.2 Incremental without zero reference. Nevertheless, in many applications the incremental encoder represents a nearly ideal solution to the encoding problem. For example, incremental encoders without zero markers are used in many x-y plotters. In this application, the encoder is used in the “floating zero” mode because the counter rather than the encoder defines the zero point by being cleared and zero-set on command.

5.10.1.2.2 Absolute encoders. The second family, the absolute encoders, are considerably more complex in construction, since the encoder delivers not only the smallest increment or bit of shaft angle rotation, but a complete word defining the location of the least bit sensed. The principal advantage of the absolute encoder is that it is in effect its own counter, since it sums and simultaneously displays the total number of least bits from the zero position. The type of code in which this sum is displayed can be varied to suit the particular application. The second important advantage of the absolute encoder is that operation is independent of previous events or conditions. A power failure, for example, will prevent encoder output during the failure; but when power is restored, the encoder will again immediately provide the absolute shaft position readout. The absolute encoder is an on-demand component and needs no attention from the system until its information is required. This capability of the absolute encoder gives the designer a powerful tool for reducing complexity in his system by time-sharing the electronic circuits.

5.10.1.2.2.1 Essential electronics. The precise degree of economy that can be effected through time-sharing depends on a number of interrelated factors. There is a certain amount of electronics essential to an absolute encoder; circuits that must be used to process data regardless of the type of parent system or the output requirements. This essential circuitry can either be included as an internal, integral part of each encoder unit or the circuitry can be an external element with the output of each encoder connected sequentially to this circuitry.

5.10.1.2.2.2 Binary contacting encoders. In the case of binary brush encoders, either the self-select type of unit could be chosen which contains all anti-ambiguity selection circuitry within the encoder, or the external logic type of unit could be used where all logical operations to remove ambiguity take place in circuits external to the encoders. In practice, if less than five to eight encoders are tied into one processor, it will be less costly to use self-select encoders. Beyond five to eight encoders, however, it becomes more economical to use external logic encoders and a single external logic to which each encoder is connected sequentially.

5.10.1.2.2.3 Non-contacting encoders. In the case of non-contacting encoders, external logic units are at present almost invariably less costly than internal logic types, principally because the logic is the same regardless of where it is located; unlike the brush type of encoder where internal is different in type from external logic (brush-disc-diode logic as against solid-state logic). Rather than compressing non-contacting encoder logic into each unit, there may be a cost advantage in using external logic with even one encoder, plus additional savings when two or more encoders use external logic. Non-contacting encoders require signal processing circuits that are distinct from the logical operations. These processing circuits are used to interrogate the encoders, amplify low-level signals, detect amplitude modulated encoder outputs, and so on. Often these circuits can be external to the encoder and used sequentially for all encoders. Sometimes the circuits must be in each encoder, for example, to amplify low level encoder sensor signals before external signal processing is possible. Clearly, for maximum economy, non-contacting encoder designers attempt to develop either encoders with extremely simple internal circuit requirements or encoders that produce high-level outputs of a type suitable for external logical manipulation with minimal internal encoder circuitry.

5.10.1.2.2.4 Absolute vs. incremental. The advantage of the absolute encoder, to provide a complete shaft position readout, implies the use of many more components and, therefore, greater probabilities of failure than the incremental type. An absolute shaft position readout does not of itself certify an absolutely correct readout. To ensure accuracy, some means is required to detect when the encoder is in error. This in turn requires a method of comparing the encoder output with some other signal known to be correct, or else the use of logical manipulations. Unfortunately, a signal known to be correct is not generally available and logic techniques must be used. The best known of these in the field of contacting encoders is the generation of complementary outputs directly from the code disc within the encoder. These complements are then compared with the digit. If both true and complements are the same for any digit, an error exists. This is an extremely effective method of error detection in brush encoders. The complements checking method, when applied to non-contacting encoders, is not quite as effective because the method of bit sensing and the usual processing circuits required make for more possible failure modes, presupposing an electronically generated complement.

5.10.1.3 Resolution. The maximum resolution (counts per turn) of an encoder is essentially limited by the smallest bit that can be reliably detected by the sensing method chosen and by the attainable angular precision of the code pattern and the code sensor. Clearly, the greater the diameter of the code pattern, the greater the resolution. The increase in pattern diameter cannot, of course, be extended indefinitely, since there is always some limit on maximum size and because mechanical tolerance problems and lowered capacity to withstand extreme environmental conditions will ultimately overwhelm the potential count capacity.

5.10.1.3.1 Higher resolution. If higher resolution in a given package is desired, techniques of sensing smaller bits and increasing the angular accuracy of the pattern and pattern sensor can be developed and used. In high resolution absolute encoders, the approach that would lend itself best to high resolution requirements is optical. The tradeoff considerations or penalties in this situation would include lowered environmental capability, probable lower coding speed, still appreciable bulk, inclusion of circuitry in the encoder, and the absence of a self-check. If the resolution required is moderate (10 to 13 bit), it may be possible to use magnetic, capacitive, or inductive types. These are not as likely to be as sensitive to environment, can be built for very low inertia or very high-speed applications, and can be provided with external circuitry.

5.10.1.3.2 Lower resolution. If 10 bit or lower resolutions will do, consideration should be given to contacting types, particularly where life expectancies are not overly long and, very particularly, where cost is a major factor. As the requirement for high resolution increases without a compensating increase in encoder size, the cost and the likelihood of poor environmental resistance will experience a parallel increase.

5.10.1.3.3 Size. Encoders can be built to very high resolutions in small frame sizes provided it is permissible to generate the full count in more than one revolution of the encoder input shaft. For example, a 13-bit binary absolute encoder can be easily built by ganging a seven-bit front section with a six-bit rear section through a 64-to-1 gear reduction. This unit will turn out a full count in 64 turns of the input shaft. This approach has proved highly satisfactory and is, in fact, one of the most-used techniques for attaining higher resolutions, particularly in systems utilizing two-speed servo systems.

5.10.1.4 Encoder specifications. In specifying encoder performance or in evaluating the parameters specified for existing encoder units, the truly critical factors must be identified and analyzed. Insignificant characteristics should be given the widest possible latitude. The following parameters will usually be critical and will require special careful consideration.

5.10.1.4.1 Brush current. Often, in contacting encoders, parameters such as brush current are labeled as maximum values. The values should never be exceeded. This is because of the high probability that decreased encoder lifetime will result.

5.10.1.4.2 Sensor output. One of the most important considerations is the output current capability of each sensor. Due to the minute size of the sensors used in encoders, considerable heating can take place during even momentary overloads. Such heating can cause irreversible changes in the encoder characteristics.

5.10.1.4.3 Line capacitance. Line capacitance must be taken into account when fitting the encoder to the system. In the case of brush encoders, current limiting is provided by series resistances inserted in each output line. These current-limiting devices should be located as close to the encoder as possible to prevent surge overloads caused by line capacitance.

5.10.1.4.4 Line rise times. When line rise times cannot meet specifications because of current limiting, buffer amplifiers must be used. By programming the encoder “on” at some point in time before it is to be read, the time necessary to set lines with the current limiting can be used as a means of eliminating the need for buffer amplifiers. Some specification limitations exist only because necessary testing to verify performance has not been accomplished.

5.10.1.4.5 Commutation. Some types of encoders must, by their nature, commutate while other encoders do not. Care must be exercised in the application of encoders to be certain that no encoder is forced to commutate when it is not designed to do so.

5.10.1.4.6 Specification checklist. System requirements for encoders must be specified at the earliest possible point in a program or project. This can often make the difference between highly successful encoder/system integration and a piecemeal, unsatisfactory patchwork of almost adequate second guesses. When properly fitted to the system, encoders provide reliable, economic, and flexible transducers in the interface between the computer and the operating equipment. The important encoder characteristics that must be considered in preparing or evaluating a specification are summarized in Table XLI.

5.10.2 Tradeoffs.

5.10.2.1 Tradeoffs - general. In selecting or designing encoder hardware, regardless of family, type, or category, certain considerations of reliability, service life, accuracy, and resolution are basic. These factors must be traded off within the confines of a general design approach to resolve hardware details and derive the exact encoder configuration required for a specific task. In the following discussion, each tradeoff factor is presented, evaluated, and its relationship to other factors and overall encoder capability explained.

5.10.2.2 Maximum life versus reliability. Reliability should not be confused with maximum life. A statement or requirement of “revolutions life” is often used as a substitute for more precise specifications defining reliability. There are several reasons why reliability expressed in “revolutions life” is neither sufficient nor correct. First, the concept of revolutions life, taken as an isolated characteristic, ignores resolution. For example, an encoder with seven bit per turn (128 counts) resolution must run at twice the speed and last for twice as many revolutions as an eight-bit per turn (256 count) encoder for the same output count in a given number of degrees rotation of the input function. This can easily be seen in the example shown on Figure 130. For this reason, an eight-bit per turn encoder with five million revolutions life is more reliable than a seven-bit per turn encoder with 10 million revolutions life. A more accurate specification for reliability can be stated as the product of the maximum revolutions life multiplied by the total counts per revolution (resolution).

5.10.2.2.1 Life. When reliability is expressed in “revolutions life”, the error rate or noise level during life and at end of life is not considered. Error rate is determined by encoder noise, together with the characteristics of associated storage circuits. For a given contact noise level, a change in storage circuit design can alter the error rate by a factor of 1,000 or more. Contact materials which produce moderate noise in early life can have less wear and longer life than materials with much lower noise levels during early life. Storage circuits which are designed to operate error-free in the presence of moderate noise can significantly increase the life of the system.

5.10.2.2.2 Temperature extremes. Reliability must take into consideration temperatures encountered during life. contact noise, contact wear and life are greatly influenced by the surface properties of the contact materials. These surface conditions are greatly altered by chemical reactions with lubricants introduced during manufacture, with wear products, and by the surrounding atmosphere. These reactions are profoundly influenced by temperature. At low temperatures lubricants can become highly viscous. Inversely, at high temperatures lubricants can decompose or react with wear products. In either case the life of the encoder is reduced. A lubricant selected to be stable at high temperature may be too viscous at low temperature. A specification of life expectancy should state the relative proportion of the total life that the encoder is to encounter under maximum temperatures, minimum temperatures? and moderate temperatures. Additionally, it should state the value of these temperatures.

5.10.2.2.3 Reliability measurement. Encoder reliability can be defined as the probability that the observed or stored value of the output is exactly equal to the input shaft position with an error not exceeding the specified accuracy. This definition does not permit a simple measurement technique. For this reason reliability is usually measured separately from accuracy and at a high repetition rate related to the maximum shaft speed of the encoder. The time between samples must be small compared to the time required for the shaft position to change one quantum (quantum time).

$$\textbf{QUANTUM TIME} = \frac{1}{\textbf{Speed (rps)} \times \textbf{C}} \textbf{(SECONDS)}$$

Where C = counts per revolution (resolution).
Under these conditions when successive samples occur at a rate greater than the encoder count change rate, reliability equals:

$$\textbf{Reliability} = \frac{\textbf{Sample rate}}{\textbf{Error rate}}$$

5.10.2.3 Reliability factors. The external factors influencing encoder reliability are maximum operating speed, time and conditions of use, and design of sampling and storage circuits. It is generally true that encoders are less reliable when operated at high speed. It is also true that an encoder experiences greater wear when operated at high speed. Even a new encoder is less reliable at high speed, and for this reason the system designer should favor choices that limit the maximum speed of the encoder. Any choice that minimizes peak speed usually also reduces average speed and, therefore, doubles life and triples reliability. In considering maximum speed, there are four basic tradeoff considerations: velocity, resolution, disc diameter, and transition accuracy.

5.10.2.3.1 Velocity. The maximum rate of change (velocity) of the phenomenon to be encoded is usually determined by system performance specifications, but the designer should be aware of the tradeoff between maximum performance and reliability. The resolution with which the phenomenon is to be encoded should be equal to or twice the required accuracy of measurement, but no greater. Increasing resolution unnecessarily only reduces the reliability of the system. The ratio of encoder resolution (counts per turn) to disc diameter should be considered, especially for contacting devices. With contacting encoders the ratio of resolution (C) to disc diameter (D) is in the range:

$\frac{C}{D}$ = 200 to 600	**Gray code** **Cyclic decimal code** **U-scan, 2-bit selector**
= 100 to 300	**V-scan** **U-scan, 1-bit selector**
= 50 to 200	**Self-selecting V-scan**

5.10.2.3.2 Resolution. The ratio of resolution to disc diameter (C/D = counts per inch of diameter) is important since reliability is influenced by the surface speed (inches per second of the contact on the disc rather than directly by rpm).

5.10.2.3.3 Disc diameter and transition accuracy. Disc diameter, hence peak surface speed, hence reliability is also influenced by the requirements for transition accuracy. For maximum reliability transition accuracy should be no greater than that required by system accuracy specifications. A practical, yet not inexpensive, specification of transition accuracy is:

C/D = 1,000 X Peak Transition Error

when transition error is specified as a fraction of a count. Combining this rule with the rule for resolution/diameter, it can be seen that, as a rule of thumb, if peak transition error cannot exceed ±0.2 quantum, the use of Gray code, cyclic decimal code, or a 2-bit selector for U-scan no longer minimizes the size of the encoder or maximizes the ratio of C/D.

5.10.2.3.4 Reliability at high speed. It is not known in a quantitative way exactly how error rate increases with surface speed. A continuing effort is being made to improve reliability at high speed. This involves improved surface finish of the disc, improved mechanical design of the contacts, redundant contacts, and improved lubricants. At the present time, a surface speed of 20 inches per second is not excessive. However, speeds of 100 inches per second or greater should be avoided. High encoder speed also influences the design and reliability of the encoder sampling the storage circuits. In this area the important parameter is not inches per second, but quanta per second. As the quanta per second increases, the speed of response of the sampling circuits must increase. Consequently, there is less opportunity for filtering or integration of the encoder signal. If latches are used, the latching period becomes shorter. As the speed of response of the sampling circuits increases, the probability of properly storing a noise pulse becomes greater. These reasons further reinforce the desirability of setting realistic limits on the maximum rate of change and the resolution of the phenomenon to be encoded.

5.10.2.3.5 Maximum quanta rate. Maximum quanta rate (quanta per second) also becomes important when using long cables between the encoder and the storage register. If the time to charge the cable capacitance becomes long compared to one quantum time (the reciprocal of the quantum rate), it becomes necessary to relocate the storage near the encoder or to employ a monostrophic code. If a monostrophic code is used, it is only necessary that the difference between capacitance charging times within the cable be small compared to the minimum quantum time.

5.10.2.3.6 Encoder wear. Encoder wear also has a profound effect on reliability; and these wear factors, especially in contacting encoders, must be carefully considered in the design and selection process. The effective contact length increases with wear. In a well-designed encoder, this increase takes place very slowly after the initial run-in period. Increase in contact length increases transition error, but does not affect reliability until transition error exceeds one-half quantum or more. This is seldom a serious problem. As an encoder wears, the contact pressure becomes less. A new encoder contact is deflected 0.015 inch to 0.040 inch (depending upon design) so that considerable wear can be sustained. Change in deflection is a problem only after many years of service, or if the encoder is manufactured with improper contact deflection when new. As an encoder wears, the wear particles react with the environment to form a non-conducting “sand” that interferes with contact between the contact and disc. These wear particles produce intermittent noise that is only eliminated as the particles are caught up and retained by the lubricant in a sort of dike along the contact path. Periodic cleaning and lubrication reduces the effect of this type of wear. Recent developments with improved metal surfaces and improved lubricants show promise of reducing this type of wear to negligible proportions. This type of wear is related to speed and to maximum and minimum temperature effects on the lubricant.

5.10.2.3.7 Lubricant failure. The most serious form of wear results from a local failure of the metal surface of the disc and the lubricant. It usually starts at the edge of a segment on the disc and results in galling or flaking of the surface of the disc. Relatively large portions of the disc may be transferred to the brush. The end result is rapid wear and early failure. This type of wear is initiated by local heating, due to a combination of high speed, rough surface, and failure of the lubricant. The lubricant can fail from decomposition at high ambient temperature or from excessive viscosity at very low ambient temperatures. This type of failure can be predicted by an analysis of the variability of the error rate during the early life of the encoder.

5.10.2.4 Electrical desire factors. The following rules form a basis for good design of encoder storage and sampling circuits. Although compromises are possible to reduce cost when the ultimate in reliability is not required or when the encoder operation is at low speed in a favorable environment, a review of these guidelines is recommended in any application of encoders using sliding contacts.

5.10.2.5 Voltage limits. The voltage across an open encoder contact should not exceed a maximum of 30 volts and preferably be limited to 3 to 10 volts. The upper limit may be exceeded providing U-scan or V-scan circuits are designed in which static switching elements, not the encoder contacts, make and break the circuits. In this case, the maximum voltage limit is set by the design of the static switching circuit. Minimum supply voltage is limited principally by the number of diodes in series in the circuit design chosen, and by the amplitude of externally generated electrical noise present in the cabling associated with the encoder and storage circuits. Although encoders are binary devices and are much less susceptible to noise than analog transducers, nevertheless, reasonable consideration must be given to noise suppression including such items as the use of twisted pair conductors to avoid magnetic coupling, use of shielding to avoid capacitive coupling, use of common grounds, and isolation and filtering of power supply sources. Additionally, heavy current pulses in the ground return circuits must be avoided.

5.10.2.6 Current limits. Electrical erosion (wear) of contacts is roughly proportional to the energy in the electrical discharge (energy is the time integral of the product of the instantaneous voltage and current) multiplied by the number of times the current is interrupted. There is, however, a lower limit of energy at which negligible electrical erosion takes place. This condition results if there is insufficient energy to raise the contact surfaces to a critical temperature, or if most of the energy is dissipated in the bulk circuit resistance, or both. In any event, electrical erosion is minimized if contact currents are limited to 0.5 to 2 mA. Higher currents to 5 mA can be tolerated if the sampling circuits are designed so that power is applied to the encoder only when it is sampled and if the sampling interval is less than one percent of the interval between samples. If U-scan, V-scan or decimal encoders are used in which static switching elements, not the encoder contacts, make and break the current, then the encoder contacts can be designed to carry 100 mA or more at the output .

5.10.2.7 Contact resistance. An encoder contact is a binary element and, therefore, associated circuits are required only to decide whether the contact is opened or closed. Although encoder contact resistance is normally less than one ohm, conservative design practice provides a margin for reduced contact force due to wear, acceleration or vibration and for the series resistance of associated wiring and cabling. A good rule is to design the storage or decision-making circuits so that in the worst case any encoder circuit with a resistance of less than 200 ohms is interpreted as a closed contact. Similarly, the resistance of an open encoder contact is normally greater than one megohm; nevertheless, conservative design practice specifies that in the worst case any encoder circuit with a resistance of greater than 5,000 ohms should be interpreted as an open contact.

5.10.2.8 Polarity. There is minor reduction in electrical erosion if the disc is made positive with respect to the output brushes. Naturally, if this is done, the common contacts are positive with respect to the disc. These contacts do not make or break current and are usually at the inside diameter of the disc and, therefore, usually have less wear than the other contacts.

5.10.2.9 Sampling circuits. Wear is reduced and reliability is improved if power is applied to encoder contacts only during interrogation. Sampling circuits designed to this rule also are necessary if outputs from two or more encoders are to be connected to a common data bus. Particular attention should be given to any amplifiers used to energize the lead and lag commons to ensure that both commons are deenergized except during the sampling interval.

5.10.2.10 Capability summary. The results of some reliability testing of state-of-the-art encoders of various types are presented here to provide a general basis for comparison and as a capability summary. These test results are by no means figures of ultimate reliability and merit, and increased performance can be expected as the results of design and manufacturing improvements are incorporated into hardware units.

5.10.2.10.1 Contact encoders. Brush encoders have demonstrated the ability to run well beyond 7,600,000 turns at 200 rpm, continuously monitored for error while being interrogated 5,000 times per second. The total time required to run 7,500,000 turns in an accelerated test at the maximum encoder speed was 625 hours. Errors occurred on the average about once in each 16,000,000 interrogations. The mean time between failures (MTBF) was 16,000,000 turns for a sample of six encoders tested under these conditions. These encoders were tested for, and are currently used in, fire control and navigation systems in U.S. Navy submarines. Other brush encoders of a different type have been tested on an autocorrelator for a rated lifetime of 2,000,000 turns. These encoders were required to operate in a severe environment where a difference of 140 millivolts was the margin between good data and errors in the worst case condition. Six encoders in a particular sample went to a MTBF of approximately 4,000,000 turns under the test conditions. These encoders were interrogated at a rate of 6,000 times a second. During the entire test period, stretching over some three months, the encoders were interrogated at a rate of 6,000 times a second; and the encoders were interrogated without error approximately 850,000,000 times. Pin contact encoders have demonstrated service life and reliability characteristics equal to, and in some cases better, than that shown for brush contact types. In addition, the test performance of pin contact units indicates superior resistance to environmental ambients (shock, vibration, and so on) and uncommonly high resistance to wear. Most importantly, pin contact encoders maintained extremely high accuracy levels in test sequences and showed especially good MTBF figures.

5.10.2.10.2 Magnetic encoders. Because of the absence of contacting component elements and the high environmental resistance, magnetic encoders provide good performance and high reliability. Magnetic encoders, subjected to life testing following full round of abuse in the environmental test laboratory, have been observed to operate to 500,000,000 turns with no sign of degradation. It is generally agreed that a well-designed and properly built magnetic encoder has a maximum service life limited only by bearing life. In many life tests of magnetic units, the total course of the test sequence is run without experiencing a unit failure even under extremely accelerated conditions.

5.10.2.10.3 Optical encoders. Optical units display much the same degree of high reliability and longevity experienced with magnetic encoders.

However, a second factor (aside from bearing life) limits the service life of optical encoders, and that factor is the required light source. The majority of presently available units employ miniature incandescent bulbs. Bulb life expectancy is enhanced by operating them below their rated voltage levels. Also, all filaments are in series which adds to the stability of the array by equalizing current. Nominally, 10,000 hours of lamp life can be expected with most good quality optical encoders and a bearing life up to 10,000 hours even under conditions of continuous operation at high speeds.

5.10.3 Accuracy factors, encoder error, and minimization. Encoders described in this handbook are limited to those which encode a mechanical shaft position into a digital output. As such, both contact and non-contact encoders have an input shaft which is rotated in accordance with the analog input, a method of encoding the analog information in digital form, and output leads and circuitry. Inherent in any measurement technique is the uncertainty of the results. The following paragraphs deal with both the inherent and other errors in the encoder measurement technique, general performance in terms of encoder specifications and terms, and error correction techniques. Total encoder error is composed of quantization error, transition error, error due to ambiguity, and noise error. Noise error and transition error are closely associated, but are discussed separately herein as they do not affect accuracy. As previously defined, reliability of an encoder is the probability that the observed or sampled value of the output is equal to the input shaft position with an error not exceeding the specified accuracy. This is in contrast to accuracy which is defined as equal to the sum of quantizing error, which is always less than ±0.5 the least count; (one-half minimum quantum); and the transition error, which is the measure of the sum of all errors arising from manufacturing tolerances and wear.

5.10.3.1 Quantization error. Quantization error, or round-off error, is the inherent error induced whenever a continuous, smoothly variable function (analog data) is changed by subdivision into data which has a finite number of discrete steps. Thus, in subdividing an analog input into a specified number of discrete steps, there will be a maximum possible inherent error of ± one-half the value of the last step. The value of this last or smallest step in a subdivision expressed in terms of the input angular increment is called a quantum. Accordingly, the last digit of a digitized analog value is uncertain. Probability laws indicate that any values between the above limits are equally possible and that the standard deviation sigma is equal to 0.289 times the value of the quantum. Average quantization error over a given number of readings is one-fourth of a quantum. Quantization error, and hence encoder accuracy, can be reduced only by increasing the number of subdivisions of the analog data (increasing the output count or resolution). A practical limit on increases in output count based on degradation of reliability is such that the size of a quantum should allow twice the encoder accuracy required by the system, but no more. Increasing output count is usually obtained at the expense of disc diameter and, therefore, encoder size, disc surface speed, or other life factors. Maximum quanta rate also determines maximum output cable length and design of associated circuitry. Quantizing error is also defined as the inherent degradation associated with digitizing an analog shaft position (round-off error). Quantizing errors may vary from -0.5 to +0.5 minimum quantum with all intermediate values being equally likely. The standard deviation sigma of quantizing error is 1/12 quantum. The probable quantizing is one-fourth that observed in half the samples. Quantizing error is fixed error and can only be reduced by increasing the resolution of the digital output count.

5.10.3.2 Transition error. Transition error is the measure of all manufacturing errors or tolerances and wear, and is also known as instrument error. Manufacturing and tolerance errors include errors in the master disc pattern, plating accuracy of the disc, and concentricity of disc rotation. Concentricity of rotation in turn depends on disc manufacturing accuracy, bearing quality, shaft runout and perpendicularity. Errors due to wear include bearing wear, brush and disc wear for contact encoders, and gear wear in multi-turn encoders. The sum of these errors is comparable by measurement of starting and running torques. Encoders which have comparably high running or starting torques may well have reduced life due to wear. The net result of transition error is that a count transition occurs at a shaft angle different from the theoretical shaft angle. Due to the wear factor in transition error, it is not necessarily constant throughout encoder life. Assuming transition errors have a normal Gaussian distribution but with the peak error limited to three times the standard deviation, one-half of the errors increase toward a negative count and the other half toward a positive count. Therefore, encoders (especially developmental models) should be operated for a period of time before a final encoder accuracy is determined. Thus , encoder accuracy is specified on a life basis. For brush type encoders, peak transitional error may be considered:

$$E_{Tpeak} = \pm \frac{C}{1000 \times D} \text{ quantum}$$

where C = counts per turn

D = disc diameter (inches)

Transition error is the difference between the theoretically correct angle of the input shaft and the actual measured angle at which the output changes from one numerical value to the next. Both the theoretical angle and the measured angle are referenced to a zero position that is halfway between the upper and lower transitions of the zero code output or a specified reference position. Transition errors can be assumed to have normal statistical distribution, but with the peak error limited to three times the standard deviation. As an encoder wears, half the transition angles shift toward zero. These are contacts which come on as the shaft is rotated in the direction of increasing count. Inversely, the other half of the transition angles shift away from zero. Most encoders are run-in so that the major change in transition angle occurs before calibration. In a well made and properly lubricated encoder, transition error increases very slowly with life. Transition errors in an encoder are the sum of:

a. Errors in the master pattern.

b. Over or underetching or over or underplating.

c. Pattern non-concentricity with axis during rotation of shaft.

d. Contact misalignment.

e. Variations in the length of contacts due to manufacturing tolerances, or wear, or both.

These factors also influence costs and these factors are subject to change as manufacturing and design are improved. As a rule of thumb, a practical transition accuracy for brush encoders can be estimated from:

$$\text{PEAK TRANSITION ERROR} = \pm \frac{C}{1{,}000 \times D} \text{ quantum}$$

Where C = count (quanta) per 360°
D = diameter of disc

For example, if: C = 800 counts per revolution

and D = 2-inch diameter disc

then: $$\text{PEAK TRANSITION ERROR} = \pm \frac{800}{2{,}000} = \pm 0.4 \text{ quantum}$$

5.10.3.3 Ambiguity. Ambiguity is the inherent error in encoders caused by the fact that two on-off measuring devices cannot be made to transfer states at precisely the identical instant each and every time. Consequently, the output is doubtful or ambiguous. Consider a hall with two individually switched lights and two children, one at each switch, trying to maintain only one light illuminated. No matter how they try, at some time both lights will be illuminated or both will be off. Similarly, two sensors in an encoder cannot switch simultaneously each and every time. If the requirement is for simultaneous switching, the error is inherent. Fortunately, errors due to ambiguity can be corrected by proper design. Methods of correcting ambiguous encoder outputs are discussed below. Since the selection of a nonambiguity technique may determine minimum encoder size, care should be taken to assure manufacturing capability.

5.10.3.3.1 Monostrophic codes. Monostrophic codes, or unit-distance codes, are a basic method of preventing inherent ambiguity. These codes require only one digit to change to effect the next successive digital output (as opposed to polystrophic codes). Only one measuring device (photocell, brush, or other sensor) is required to change the on-off state at any one time, eliminating inherent ambiguity of massive error. Error can still occur in the single digit change, but is easily detected. Codes of this type are discussed in the section covering numbering systems, binary codes, and coding under nonweighted binary codes.

5.10.3.3.2 Window code. A window code is a code which prevents any encoder readout during the transition between numbers. ambiguous outputs are prevented by restriction of the readout time. window codes are a form of detent and are usually electrical. Thus, by adding a window track to a coded disc and requiring that the window output be "on" before any data is read, transition time is electrically eliminated from the readout. A typical contact-type coded disc utilizing window code is shown on Figure 51. The outermost track of the disc is the window.

5.10.3.3.3 Lead-lag techniques. The lead-lag (advance-retard) techniques are methods of prohibiting transition point ambiguity of a polystrophic code by using spaced brushes or sensors, and possibly additional tracks, for each digit. Output is taken from either sensor for a given digit as selected by logic circuits or as keyed by encoder output. The brushes or sensors are electrically or physically spaced at one-half the total minimum bit width. The sensor selected for readout is at least one-half the minimum width away from a transition point, eliminating ambiguity. For optical encoders, a disc mask can be used to perform the lead-lag selection. Many different lead-lag techniques exist. All require additional circuitry, either inside the encoder, in the form of external logic, or more strict manufacturing tolerances for the coded disc. Choice of a specific technique is a tradeoff and must be interpreted in terms of system requirements and accuracies.

5.10.3.3.4 V-scan. The V-scan technique is a method of obtaining nonambiguous outputs from a polystrophic encoder by utilizing two sensors for each bit of disc information except the LSD. This method is named from the V-like pattern of the staggered sensors as shown on Figure 131. Selection of the proper sensor for readout of a given bit is determined by logic circuits which sample the state of the previous LSD. If the logic determines that the previous LSD was a logical "0", the leading sensor for the given bit is selected for readout. Conversely, if a logical "1" existed in the previous digit, the lagging sensor for the given digit is selected for readout. Therefore, the V-scan technique normally proceeds serially, LSD first. The term leading or lagging is determined by the position of the brush relative to the reading line and the relative direction of shaft motion. Changing the direction of encoder rotation also changes the sensor terminology. The reading line, which is the position of the LSD sensor, is the actual shaft position being read. The V-scan technique can also be accomplished by modification of the disc (V-disc). In the V-disc modification (Figure 132), the sensors are operated in line with the disc tracks staggered. In-line operation for contact encoders allows a stronger, more durable brush assembly. Logic equations and diagrams for the V-scan technique are included in another portion of this handbook. A typical contact-type disc for the V-scan technique is shown on Figure 133.

5.10.3.3.5 Self-selecting V-scan. The self-selecting V-scan technique is used where lead-lag sensor selection must be performed within an encoder due to external scan matrix limitations or nonavailability. Self-selection of the proper sensors for a given disc track is accomplished by placing sensors in series, generating NOT logic functions, and using the previous LSD track data to key the given track. These logic relationships are discussed elsewhere in this handbook. Self-selecting V-scan generates both bit and complement simultaneously as in the external scan matrix, but accomplishes the logic selection by using four sensors, three tracks, two diodes, and relatively high power supply voltages. To minimize the total number of tracks, self-selecting V-scan encoders utilize staggered sensor arrangement such that a single track can provide both the lead and lag functions.

5.10.3.3.6 M-scan. The M-scan technique is a variation of the V-scan technique and is used in applications where processing equipment can more easily process complements of the V-scan logical output. By obtaining a complemented output directly from the code disc, the additional circuitry required for complementation of V-scan output is eliminated. The M-scan feature is obtained by defining the normal lag brushes as a NOT function. As in V-scan techniques, M-scan can be accomplished by the M-sensor configuration or by in-line sensors and an M-disc. An M-disc is shown on Figure 57 with the track assignment.

5.10.3.3.7 U-scan. The U-scan technique is a lead-lag technique for obtaining nonambiguous outputs that allows a reduction in angular manufacturing tolerances of the disc tracks. U-scan is usable with all codes and number systems, but differs from other lead-lag techniques in that the LSD is used to select a group of MSD’s rather than only the next MSD. In this manner, the normally required complement generation for advanced tracks is eliminated. In particular, U-scan or equivalents must be used for BCD codes as V-scan cannot be used exclusively. A typical U-scan disc is shown on Figures 134 and 135. Note that tolerances for the higher order tracks, those most normally critical as the diameter is small, are reduced since they are not effectively energized until the LSD is present. Additionally, no restriction is placed on track location for a particular digit. The lead or advance sensors and tracks are of one group and the lag or retard sensors and tracks are a second group. Figure 136 shows the U-scan technique using two groupings to increase manufacturing tolerances. The groups are referred to as belts, with the alpha or selector belt nearest the edge of the disc and the beta belt near the disc axis. Manufacturing tolerances on the second belt vary with the number of first belt bits used in the codes. (Bits used for selection but not part of the code reduce resolution and manufacturing tolerances by one-half.) By using two bits on the first belt, tolerance is increased by four. Similarly, three alpha belt bits give a tolerance reduction of eight. U-scan is particularly useful in a multi-turn encoder where, by selecting the slow disc bits from the fast disc, gear backlash errors are eliminated.

5.10.3.3.8 Combination and other scan techniques. Combination techniques and variations of the lead-lag antiambiguity techniques are used. In multi-turn units, a window code may be used on the high-speed disc and U-scan on the low-speed disc. L-scan or T-scan are also available. For BCD encoders, a combination of U-scan and V-scan is used. The selector bit may be the LSD or generated from a separate track. Ninety degree phased discs may be used in multi-turn units. In this case, the external computing circuits compare the overlapping bits to determine which disc to read. Intermediate motion gearing is possible on multi-turn monostrophic encoders.

The net result of all ambiguity techniques is an encoder output free from errors due to code selection.

5.10.3.4 Noise error. Noise error occurs in contact-type encoders and is the error caused by any variation in the steady state resistance of an encoder contact. Most noise error is edge noise occurring at transition points as a sensor switches from “On” to “Off’* or “Off” to “On”, although dropouts in the center portion occur also (but at a ratio of 1,000 to 1). Since encoders have current flow only during “On” conditions, the “True” or “1” signals are noisy. Noise error is the sum of contact wear (a form of transition error), encoder design in terms of materials or lubrication, and operating conditions such as reading voltage and current. Error rate is the frequency of errors appearing in the output due to both encoder error and storage or readout errors. By proper design of both encoder and readout circuits, any errors due to noise can be minimized to insignificant proportions for most applications. Some design factors are discussed as follows.

5.10.3.4.1 Electrical considerations. Contact-type encoders require consideration of reading voltage, current, load characteristics, and polarity. In all cases contact voltage should be restricted to the minimum required for readout (overcoming forward resistance of diodes). Voltages between 3 and 10 volts are preferred, and not more than 30 volts for all encoders that utilize the contacts for actual conduction. With lead-lag ambiguity circuits having static switching elements, the voltage is limited by the switching element characteristics. For direct readout, current through encoder contacts should be less than 5 mA, preferably between 0.5 and 2 mA. If sampling techniques are utilized, contact currents can exceed 100 mA. This is due to the fact that contact wear is an energy-time function, not current. Higher currents for shorter durations at the same voltage yield a similar energy transfer (similar area under the instant voltage-current-time integral). At the lower values of current, contact surface temperature is below that at which erosion of contacts becomes a consideration. Contact wear, electrically, is related to total volt-amperes being switched. Low voltages and low currents below the erosion threshold are, therefore, essential to long life. If sampling techniques are to be utilized because of high volt-ampere requirements, designers must consider minimum storage time and charging requirements of output cables. If no error is to be permitted in monostrophic codes, sampling times must be less than one-fourth quantum time for systems not utilizing storage. If storage is used, response time must be less than the minimum quantum time for a no-error output. With polystrophic codes, antiambiguity logic and storage sampling time must be much less than one-half minimum quantum time. Otherwise, the change from lead-to-lag brush readings would e read into storage. Loads into which contacts discharge energy should be resistive. Extreme inductive or capacitive loads can reduce contact life to zero. As presented in other texts, common circuits (disc) should be of positive polarity to minimize contact erosion. Since all sensor-disc surfaces have a contact resistance, external circuit design should register True for contact resistances of 100 to 200 ohms or less and False for contact resistances of 5,000 ohms or greater. Closed circuits normally measure 0.1 ohm or less of contact resistance while open contacts are at least 1 megohm. Thus conservative design of external circuits allows a margin of 10,000 (minimum) in the event of erosion and increased or decreased contact resistance.

5.10.3.4.2 Encoder signal-to-noise ratio. As in communications fields, receptors should have a bandwidth slightly less than the information received; no more, no less. A greater bandwidth allows more noise; a lesser bandwidth allows loss of information. Since encoder signals are a relatively low frequency signal, good use can be made from clipping and filtering techniques. As with other systems, bandwidth is limited by the highest frequency component required to pass onto ensuing circuits. For encoders, this is the minimum quantum time or sampling time, whichever is less. Signal-to-noise ratio is important in non-contact encoders, as well as in contact encoders. For magnetic units, ratios of 30 dB can be obtained under ideal conditions. For production units with several tracks, ratios between 15 and 24 dB are typical. Accurate determination of signal-to-noise ratio precludes specific definitions of logical “1’s” and “0’s” upon which the ratio is based. Similarly, optical encoders also have a signal-to-noise ratio. When the ratio drops below 10 dB, readout becomes marginal for accurate detection purposes. Low signal-to-noise ratios in optical encoders are caused by excessive disc-to-sensor spacings, light diffraction, high reverse current conditions in photo cells or sensors, low illuminations, or difficult resolution requirements. Poor ratios become a function of encoder resolution with powers of two beyond the thirteenth, but with satisfactory encoders being produced above 2^{18}. For greater resolutions, electronic derivation of the LSD’s can be used. Techniques in use are Beamscan, Phasescan, and digital phase-locked loop techniques.

5.10.3.5 Reliability checking. Encoder reliability is defined as the probability that encoder output is equal to the mechanical input within the specified encoder accuracy. Reliability takes into account the auxiliary circuits used with the basic encoder for all environments and rated conditions, while accuracy specifies characteristics of the encoder itself. Reliability is usually checked by sampling encoder output many times during a single quantum time, where a quantum time is the time required for the input shaft to change one count.

Thus: $$\text{Quantum (sec)} = \frac{1}{\text{Speed (rps)} \times C}$$

Where C = counts per revolution

And then: $$\text{Reliability} = \frac{\text{Sample rate}}{\text{Error rate}}$$

Reliability in general is affected by encoder speed, resolution, disc diameter, LSD segment length, environmental conditions, and design of output circuits. Methods of increasing reliability are discussed in the following paragraphs.

5.10.3.5.1 Latch techniques. The latch technique is a method of reducing contact-type encoder error by eliminating dropouts during encoder “On” time. Two control signals, a filter, an AND gate, and an OR gate are required for each encoder digit so protected, the logic for which is described in the logic section of this handbook. Basically, a control signal clears all logic circuits where they await a first indication of a "True" signal. When a logical "1" appears, it is passed to the output through a one-fourth quantum filter. The signal on the output is fed back to the input where it maintains the logic circuit in a True condition despite any variation in encoder contact resistance. Latch circuits are used with only momentarily noisy encoders, as the filter cannot discriminate between noise and signal. Latch circuits used with noisy encoders actually decrease reliability and accuracy.

5.10.3.5.2 Clipping and filtering. As shown on Figure 137, an idealized contact encoder signal typically has edge noise, and may have a partial dropout in the main portion of "On" time. Through the use of a resistance-capacitance filter, areas under the curve are partially integrated, raising the edge noise and fallout toward more positive levels. The filter raises the average component so that a following clipper can have a higher output level for the same input signal. Filters typically have a fast rise time to "True" signals, and a relatively slow discharge time to "False" signals. Depending on the maximum information rate, a critical time constant is derived. This constant is nominally one-half the sampling interval if used, or between 0.1 and 0.3 of the minimum quantum time. Rise time response to "True" or "1" signals is then set at approximately 0.025 of this time constant and the fall time at 0.250 of the time constant. It should be noted that if excessive noise is present in the encoder output, filtering and clipping serve no useful purpose as they operate because of the ratio of peak-to-average signal levels and actually do not discriminate between noise and signal, except by the varying repetition rates relative to average rate or charge.

5.10.3.5.3 Sampling techniques. Sampling techniques are methods of increasing encoder reliability by restriction of interrogation rate or time, and by limiting sensor power to actual interrogation time. Interrogation is controlled by a sampling pulse to obtain a readout. Sampling is required in multiple encoder time-shared systems and may be desirable in contact-type encoder systems. Selection of sampling pulse lengths (widths) may determine the characteristics of other reliability increasing techniques. When used in combination with clipper-filter techniques and the sampling pulse is short compared to a quantum time, the minimum rise time of the filter is governed by the sample pulse width. If a long rise time filter is desired while using short length sampling pulses, an additional, continuously energized, low-power selector bit may be incorporated in the encoder. Selection of a sampling technique must be based on the sampling time-quantum time ratio, the code in use, encoder speed, error rate allowable, ambiguity technique in use, and system cable capacitances. With monostrophic codes, maximum allowable delay due to charging of cable capacitances must not exceed one-fourth quantum time or accuracy will not be maintained. Excess cable capacitance in system will require storage registers to obtain workable systems. With polystrophic codes and with ambiguity techniques, manufacturing tolerances on minimum quantum widths are reduced and thus place additional time restrictions on contemplated storage. Additionally, the selector bit must be stored first to avoid reading the wrong combination of lead-lag sensors into storage, and effective cable capacitance is increased as more than one bit changes for a given adjacent readout. Accordingly, time requirements for storage in polystrophic encoders are less, and the time required to store the first two least significant bits (LSB's) must be less than one-half the minimum quantum time. Sequential storage for V-scan techniques is required unless both lead and lag sensors are stored.

5.10.3.5.4 Set-Reset technique. Set-Reset techniques (logic) may be used to increase encoder signal-to-noise ratio and hence reliability. Set-Reset logic operates on the principle that if an encoder output is noisy, readout reverts to the previous readout until the noisy sensor has been cleared. Two overlapping sensors on the LSB track generate the necessary data. Logic circuits for Set-Reset logic are covered in other portions of this handbook.

5.11 Selection of an encoder.

5.11.1 Encoder characteristics - general. The selection of an encoder or encoder characteristics to perform a given task may become a problem in that trade-offs must be made. A minimum of items below must be considered to assure logical selection of a unit. To act as a guide, probable limitations in selection imposed by the state of the art are shown in Table XLII. Encoders actually produced may differ considerably from the state-of-the-art units due to development and new manufacturing techniques. Not only should the tables be consulted in selecting an encoder, but manufacturers should be contacted also. The following criteria is necessary to specify encoders:

a. Output notation.

b. Output code.

c. Antiambiguity logic.

d. Physical limitations.

e. Electrical requirements.

f. General characteristics.

5.11.1.2 Selecting output notation. The output notation required may well determine the output code to be used. Any desired output notation can be coded, and in some cases, new codes must be created to obtain a monostrophic code or a code that is easily complemented. Output notation may be linear, square root functions, trigonometric, nonlinear, or random.

5.11.1.3 Selecting output code. Output codes are regularly weighted, non-weighted, or arbitrarily weighted. Within the regularly weighted group, natural binary, incremental, BCD codes, and others may be chosen. Natural binary is the most compact code and utilizes all possible code combinations for the digits available. Incremental code is easily reset to zero and has very small torque requirements. The code is useful for rate information. The BCD is very easy to process. It is comparable to the decimal system and is ideal for error checking and correction. Using these codes, heavy current loads can be driven and arithmetic operations performed easily. Encoders using these codes can be operated in parallel with a minimum of additional circuitry. However, power consumption is high; circuits are more complex; and torque and inertia requirements are higher due to additional brushes or sensors. Additionally, storage time, physical size, or storage is increased. Cable capacity requirements become more stringent if parallel readout is required as more than one line must be energized in going to any successive number. These codes are polystrophic. As such, they require antiambiguity logic, a further increase in torque requirements. As a result of some types of antiambiguity logic, readout is restricted to serial operation unless two storage registers are used. If sampling techniques are used, sampling time is restricted by lead-lag brush techniques. In the nonweighted group, cyclic or reflected cyclic codes exist which are monostrophic. These codes are nonambiguous by definition and have high resolution. In multi-turn encoders, high resolution allows a reduction in gear ratios reducing gear backlash problems. Disc size, with the consequent reduction in inertia and torque requirements is also affected. As disc size reduces, brush surface travel reduces, increasing contact life for any given disc speed. With monostrophic codes, bits may be stored in parallel, simultaneously, without the added storage required by polystrohpic codes and stored at a faster rate. Cable capacity considerations are lessened as only one bit changes for each successive number. On the other hand, monostrophic codes require additional circuitry for arithmetic operations and must carry full load current across the contacts. Sampling circuits may be required to increase encoder life. In either group, error checking codes can be assigned. Where addition, comparison, or storage is not required (such as direct printouts or typewriters), the direct decimal code, or an almost equally effective biquinary decimal or alphanumerical code, may be chosen at an increase in size and cable requirements. If comparison or arithmetic computations are required, external computing circuits work best with a binary coded decimal code. In special applications such as negative-positive readouts or for simplification of antiambiguity logic, combination codes can be chosen such as the ICAO (formerly MOA-Gillham) code which is a combination of two cyclic codes. In short, code selection is a trade off and must be examined in terms of the entire system.

5.11.1.4 Selecting antiambiguity logic. If a polystrophic code is required, some form of antiambiguity logic must be chosen. Since antiambiguity logic requires more sensors and more tracks on the coded disc and varies with the logic chosen, encoder size may be adversely affected by an improper choice. By proper choice of antiambiguity logic, the extra functions required can be minimized in the encoder and transferred to external circuits. Alternately, if readout equipment exists, the extra functions can be transferred to the encoder, but will probably cause an increase in encoder size.

5.11.1.5 Selecting physical limitations. Physical limitations include maximum weight, case length, case diameter, shaft diameter, shaft length, shaft type, and environment.

5.11.1.5.1 Encoder size. In general, encoder size is determined by the code used, total output counts required, resolution, and transition accuracy. Synchro-type mounts have proved successful and a series of standardized synchro mounts are illustrated on Figures 33 through 40.

5.11.1.5.2 Special operating environment. Special operating environments must be specified. Encoder performance is affected by vibration, shock, corrosive atmosphere, temperature, or humidity. Vibration levels should be specified in terms of rate (cycles per second) and direction relative to the encoder axis. Similarly, the maximum shock should be specified in G's. Temperature specifications should be designated by a range of operating temperatures, including storage, as this affects lubricants used, as well as both starting and running torques. Where a combination of environmental conditions such as low temperature and vibration exist simultaneously, they should be so specified if a satisfactory encoder is to be obtained. Adverse environments as they affect encoder bearings are discussed in the following paragraphs.

5.11.1.5.2.1 High temperature. High temperature encoder environment above 350°F creates special problems with bearing life as initial lubrication (normally oil) quickly loses its lubricating value (actually vaporizes) . A special lubricant must be used, or the former lubricant continuously supplied in order to have reasonable encoder life. Limitations for available bearing materials are shown in Table XLIII to aid in encoder system design.

5.11.1.5.2.2 High vacuum. High vacuum encoder environment is similar to high temperature operation in that lubricants vaporize rapidly causing a high rate of adhesive wear. Encoder bearings for this application should be of the shielded type which may reduce internal pressures by a power of 100. Various problems and solutions for this type of environment are listed in Table XLIV.

5.11.1.5.2.3 Nuclear radiation. Nuclear radiation environments affect all organic lubricants, which appears as an increase in viscosity and a consequent increase in torque. Levels at which lubricant usefulness is destroyed varies with the lubricant as indicated in Table XLV. Although encoder bearing materials will operate in radiation environments of greater than 10^8 roentgens, no lubricants are currently available. A radiation environment also destroys encoder diodes.

5.11.1.5.2.4 Extreme low temperature. Low temperature encoder environment below -100°F again poses lubrication problems. Bearing loads must be reduced to absolute minimums, and should be operated in a glass-filled teflon retainer submerged in liquid hydrogen or nitrogen. Bearing materials are otherwise satisfactory as they become stronger with lower temperatures (slowing of molecular action). Table XLVI indicates a selection of lubricants for medium temperature operation.

5.11.1.6 Selecting electrical requirements. The following electrical requirements should be considered in selecting an encoder. (See 5.6.4.)

a. Maximum load voltage per digit.

b. Maximum load current digit.

c. Load impedance in ohms and reactive components.

d. Output signal polarity.

e. Diode location, external or internal.

f. Readout method (serial, parallel, or both).

g. Output connections.

h. Auxiliary circuits required and location (filter, buffer, storage, and so on).

5.11.1.7 Selecting general characteristics. General characteristics are usually determined by system requirements or existing situations, and the following must not be overlooked.

a. Life in revolutions at a specific temperature and speed.

b. Maximum reading speed in rpm.

c. Maximum slewing speed in rpm.

d. Transition accuracy.

5.11.1.7.1 Count characteristics and torque requirements. With the code and the majority of mechanical input characteristics determined, the following items should be considered:

a. Sense of rotation for increasing counts.

b. Number of total counts for full-scale output.

c. Amount or number of rotations for full count (single-turn or multi-turn encoder, as applicable).

d. Maximum starting and running torques within mechanical input limitations.

e. Maximum moment of inertia within limitations.

5.11.2 Selection of encoders for military use.

5.11.2.1 Specifications. Encoders for military use are described by two types of specifications, the general specification and the specification sheet. The general specification sets forth the requirements for all encoders of a specific type or classification, and the specification sheet further defines a specific encoder of the general class by stating individual requirements or by taking exception to the general specification. Specifications may be fully coordinated and used by all branches of the military or limited-coordinated and used by as few as one group of a particular branch. Other types of specifications such as the interim type are also issued as required. Specifications establish requirements for operating environments, reliability, accuracy, and life.

5.11.2.2 Military nameplate data. Encoders for military use are classified or described on the nameplate as discussed in the following paragraphs. Typical nameplate sequence of data should follow the example given in Table XLVII.

5.11.2.2.1 Item name. In all cases, the item name will be "Encoder, Shaft Angle to Digital."

5.11.2.2.2 Size. The first two digits of the type designation indicate the maximum diameter of the encoder in tenths of an inch. The next higher tenth is used for encoders whose diameter is not a whole number of tenths.

5.11.2.2.3 Type. The encoder type is the operating principle used and is designated by a single letter in accordance with Table XLVIII.

5.11.2.2.4 Code and scan. The digital output code and the antiambiguity logic will be designated by a single letter according to Table XLIX.

5.11.2.2.5 Readout. Whether the sensor selection is accomplished internally or externally, and whether the readout is parallel or serial, will be designated by a single letter according to Table L.

5.11.2.2.6 Capacity. The capacity of the encoder is designated by a two-digit number equal to the highest power of two or ten contained in the total count. Incremental will be listed as the closest power of two.

5.11.2.2.7 Function. The digital output of the encoder is usually a mathematical function of the shaft position and is designated in Table LI.

5.11.2.2.8 Resolution. The resolution of an encoder is designated by a number equal to the highest power of two or ten counted by one revolution of the input shaft. Numbers less than ten are preceded by a zero. Incremental units will be listed as the closest power of two.

5.11.2.2.9 Modification. The upper case letter "A" following the resolution designation indicates the original or basic issue of an encoder type. Modifications which affect interchangeability are indicated by a successive upper case letter, with the exception of "I", "L", "O", or "Q" which are prohibited.

	Lamp Condition		Visual Pattern		Binary Equivalent	
Shaft Position	**A**	**B**	**A**	**B**	**A**	**B**
0°	OFF	OFF	○	○	0	0
90°	OFF	ON	○	●	0	1
180°	ON	OFF	●	○	1	0
270°	ON	ON	●	●	1	1
360°	OFF	OFF	○	○	0	0

TABLE II. Typical characteristics of magnetic materials.

Material	Nominal Composition (%)					Typical Heat Treatment °C	Permeability at B = 20 (gausses)	Maximum Permeability	Saturation Flux Density B (gausses)	Hysteresis Loss, W_h (ergs/cm^3)	Coercive Force H_c (oersteds)
	Fe	Ni	Co	Mo	Other						
Cold rolled steel	98.5	--	--	--	--	950 Anneal	180	2,000	21,000	--	1.8
Iron	99.91	--	--	--	--	950 Anneal	200	5,000	21,500	5,000	1.0
Purified iron	99.95	--	--	--	--	1480 H_2 + 880	5,000	180,000	21,500	300	0.05
4% Silicon-iron	96.0	--	--	--	4 Si	800 Anneal	500	7,000	19,700	3,500	0.50
Grain-oriented*	97.0	--	--	--	3 Si	800 Anneal	1,500	30,000	20,000	--	0.15
45 Permalloy	54.7	45.0	--	--	0.3 Mn	1050 Anneal	2,500	25,000	16,000	1,200	0.30
45 Permalloy	54.7	45.0	--	--	0.3 Mn	1200 H_2 Anneal	4,000	50,000	16,000	--	0.07
Hipernik	50.0	50.0	--	--	--	1200 H_2 Anneal	4,500	70,000	16,000	200	0.05
Monimax	--	--	--	--	--	1125 H_2 Anneal	2,000	35,000	15,000	--	0.10
Sinimax	--	--	--	--	--	1125 H_2 Anneal	3,000	35,000	11,000	--	--
78 Permalloy	21.2	78.5	--	--	0.3 Mn	1050 + 600 Q	8,000	100,000	10,700	200	0.05
4-79 Permalloy	16.7	79.0	--	4	0.3 Mn	1100 + Q	20,000	100,000	8,700	200	0.05
Mu metal	18.0	75.0	--	--	2Cr.5Cu	1175 H_2	20,000	100,000	6,500	--	0.05
Supermalloy	15.7	79.0	--	5	0.3 Mn	1300 H_2 + Q	100,000	800,000	8,000	--	0.002
Permendur	49.7	--	50.0	--	0.3 Mn	800 Anneal	800	5,000	24,500	12,000	2.0
2V Permendur	49.0	--	40.0	--	2V	800 Anneal	800	4,500	24,000	6,000	2.0
Hiperco	64.0	--	34.0	--	Cr	850 Anneal	650	10,000	24,200	--	1.0
2-81 Permalloy	17.0	81.0	--	2	--	650 Anneal	125	130	8,000	--	< 1.0
Carbonyl iron	99.9	--	--	--	--	---	55	132	--	--	--
Ferroxcube III	$MnFe_2O_4$ + $ZnFe_2O_4$					---	1,000	1,500	2,500	--	0.10

TABLE III. Semiconductor characteristics.

Property	Ge	Si	GaAs	Units
Melting point	937.0	1415	1240	°C
Density (at 25°C)	5.32	2.33	5.31	grams/cm^3
Therm. coefficient expansion	6.1 x 10^{-6}	4.2 x 10^{6}	5.9 x 10-6	/°C
Thermal conductivity	0.63	0.84	0.52	watt units
Specific heat	0.074	0.181	0.086	cal/gram - °C
Atomic weight	72.60	28.09	144.6	number
Lattice constant	5.657	5.431	5.654	Å
Atoms/Cm^3	4.42 x 10^{22}	4.99 x 10^{22}	4.43 x 10^{22}	number
Dielectric constant	16.0	11.8	11.1	vacuum = 1
Band gap energy	0.67	1.106	1.40	electron volts
Intrinsic resistivity (300°K)	46.0	2.3 x 10^{5}	3.7 x 10^{8}	ohm-cm
Electron lattice mobility (300°K)	3900	1500	10000	cm^2/volt-sec
Hole mobility	1900	500	450.0	cm^2/volt-sec
Intrinsic charge density (300°K)	2.4 x 10^{13}	1.5 x 10^{10}	1.4 x 10^{6}	number/cm^3
Electron diffusion constant (300°K)	100.0	38.0	310.0	cm^2/sec
Hole diffusion constant (300°K)	49.0	13.0	11.5	cm^2/sec

TABLE IV. Semiconductor properties, various materials.

Semi-conductor	Band Gap (electron volts)	Approximate Maximum Device Temperature (°C) (Theoretical)	Dielectric Constant Air = 1	Electron Mobility, μp (cm^2/volt-sec)	Hole Mobility, μp (cm^2/volt-sec)
Ge	0.67	100	16.0	3900	1900
Si	1.106	250	11.8	1500	500
GaAs	1.40	450	11.1	~ 10000	> 450
SiC	2.80	> 1000	7.0	> 100	> 20
C (Diamond)	6.70	> 1000	5.7	~ 1800	1200
InSb	0.18	~ -196	15.9	~ 80000	~ 1000
InAs	0.33	~ - 75	11.7	~ 33000	460
GaSb	0.68	100	14.0	~ 4000	~ 1400
InP	1.25	400	10.8	~ 4600	~ 150
AlSb	1.60	500	10.0	> 400	> 400
GaP	2.40	1000	8.4	> 100	> 20
AlAs	~ 2.20	900	---	~ 1200	~ 200

TABLE V. Angular correlation.

Powers of 2	Number of Divisions	Angle per Division	Milliradian Division	Percent Resolution
0	1	360°	62.832 x 10^2	100.0
1	2	180°	31.416 x 10^2	50.0
2	4	90°	15.708 x 10^2	25.0
3	8	45°	7.854 x 10^2	12.5
4	16	22°30’	3.927 x 10^2	6.25
5	32	11°15’	1.9635 x 10^2	3.125
6	64	5°37’30”	98.175	1.5625
7	128	2°48’45”	49.0874	0.78125
8	256	1°24’22-1/2”	24.544	0.390625
9	512	42’11-1/4”	12.272	0.195313
10	1,024	21’5-5/8”	6.136	0.097656
11	2,048	10’32-13/16”	3.068	0.048828
12	4,096	5’16-13/32”	1.534	0.024414
13	8,192	2’38-13/64”	0.767	0.012207
14	16,384	1’19.10156”	0.3835	0.006104
15	32,768	39.55078”	0.1917	0.003052
16	65,536	19.77539”	0.0959	0.001526
17	131,072	9.88770”	0.0479	0.000763
18	262,144	4.94385”	0.0240	0.000381
19	524,288	2.47192”	0.0120	0.000191
20	1,048,576	1.23596”	0.00599	0.000095
21	2,097,152	0.61798”	0.0030	0.000048

TABLE VI. Typical encoder minimum sizes.

Performance Parameters				Stages	Minimum Size 1/	Diameter (inches) 1/
Bits	Counts	Turns	Bits/Rev			
7	128	--	--	Single	10	0.8
8	256	--	--	Single	10-18	0.8-1.8
9	512	--	--	Single	14-30	1.4-3.0
10	1,024	--	--	Single	23-35	2.3-3.5
11	2,048	--	--	Single	45-55	4.5-5.5
12	4,096	--	--	Single	63	6.3
9	512	2	8	2	11-18	1.1-1.8
10	1,024	4	8	2	11-18	1.1-1.8
11	2,048	8	8	2	11-18	1.1-1.8
12	4,096	16	8	2	11-18	1.1-1.8
13	8,192	32	8	2	11-18	1.1-1.8
14	16,384	32	9	2	11-18	1.1-1.8
15	32,768	64	9	2	11-18	1.1-1.8
16	65,536	64	10	2	18-23	1.8-2.3
17	131,072	128	10	2	35	3.5
14	16,384	64	8	3	11	1.1
15	32,768	128	8	3	11-18	1.1-1.8
16	65,536	256	8	3	11-18	1.1-1.8
17	131,072	512	8	3	11-18	1.1-1.8
18	262,144	1,024	8	3	11-18	1.1-1.8
19	524,288	1,024	9/10	3	18-23	1.8-2.3
20	1,048,576	2,048	9/10	3	18-23	1.8-2.3
21	2,097,152	4,096	9/10	3	23	2.3
9	±100	1	200	Single	11	1.1
12	1,000	1	1,000	Single	23	2.3
13	±1,000	1	2,000	Single	45	4.5
12	1,000	10	100	2	11	1.1
16	10,000	50	200	2	18	1.8
20	100,000	100	1,000	2	35	3.5
16	10,000	100	100	3	11	1.1
20	100,000	2,000	500	3	18	1.8
24	1,000,000	200	5,000	3	23	2.3

NOTE:

1/ Range of minimum sizes depend on coding technique.

TABLE VII. Instrument bearing classes and tolerances.

ABEC Class	Bore +0.0000 in. to Minus	OD +0.0000 in. to Minus	Eccentricity, FIM	
			Inner Race	Outer Race
1	0.0003	0.0004	0.0004	0.0006
3	0.0002	0.0003	0.0003	0.0004
5	0.0002	0.0002	0.0002	0.0002
7	0.00015	0.0002	0.0001	0.0002
9	0.00010	0.00015	0.00005	0.0001

TABLE VIII. Gear tooth manufacturing tolerances.

Gear Class	Total Composite Error (inch)	Tooth-to-Tooth Composite Error (inch)
Commercial 1	0.006	0.002
Commercial 2	0.004	0.0015
Commercial 3	0.002	0.0010
Commercial 4	0.0015	0.0007
Precision 1	0.0010	0.0004
Precision 2	0.0005	0.0003
Precision 3	0.00025	0.0002

TABLE IX. Typical encoder weights.

Encoder Description						Size	Weight (ounces)
Code	Counts	Turns	Accuracy	Max. Reading Speed	Detection		
Natural Binary	2^7	1	1/128	200 rpm	Brush Contact	11	1.1
	2^{13}	32	1/8 - 192	20 rpm	Optical	11	4.5
	2^{13}	64	1/128	200 rpm	Brush Contact	11	1.9
	2^{15}	64	1/32 - 768	1,280 rpm	Optical	18	8.0
	2^{18}	2,048	1/128	200 rpm	Brush Contact	11	2.7
	2^7	1	1/128	200 rpm	Brush Contact	18	3.7
	2^{13}	64	1/8 - 192	200 rpm	Brush Contact	18	6.8
	2^{19}	4,096	1/524 - 288	200 rpm	Brush Contact	18	10.5
	2^{19}	1	1/524 - 288	50°/sec	Capacitive	34	72.0
Binary Coded Decimal	10^2	1	1/100	150 rpm	Brush Contact	23	5.2
	360	1	1/360	90 rpm	Brush Contact	33	7.5
	10^3	10	1/1,000	150 rpm	Brush Contact	23	9.3
	360	36	1/360	150 rpm	Brush Contact	23	10.0
	3600	36	1/3,600	150 rpm	Brush Contact	23	10.0
	10^4	100	1/10,000	150 rpm	Brush Contact	23	13.2
	36,000	360	1/36,000	150 rpm	Brush Contact	23	14.2
	10^5	1,000	1/100,000	150 rpm	Brush Contact	23	16.7
	360,000	3,600	1/360,000	150 rpm	Brush Contact	23	17.0
	36,000	3,600	1/36,000	150 rpm	Brush Contact	23	18.0
	10^6	10,000	1/1,000,000	150 rpm	Brush Contact	23	20.3
Gray	2^8	1	1/256	200 rpm	Brush Contact	18	3.0
	2^9	1	1/512	150 rpm	Brush Contact	23	4.5
	2^{10}	1	1/1,024	90 rpm	Brush Contact	31	7.5
Incremental	2500	1	±30 arc sec	3,000 rpm	Optical	10	1.5
	1024	1	--	3,000 rpm	Optical	14	1.8
	3600	1	±30 arc sec	3,000 rpm	Optical	15	4.0
	2048	--	±1/4 count	3,000 rpm	Optical	23	5.0

TABLE X. Environmental resistance.

Encoder Description							Environmental Resistance			
Type	Count	Turns	Accuracy	Slew Speed (rpm)	Size	Weight (oz.s)	Shock (G's)	Vibration	Temperature (degrees C)	Other
Pin Contact	2^{13}	--	1/8 - 192	--	11	--	150	30G's, 5-2,000 Hz	--	--
	2^{18}	--	1/262 - 144	--	11	--	150	30G's, 5-2,000 Hz	--	--
Magnetic	2^{13}	64	±1/4 bit	10,000	18	--	1/	1/	-55 to +100	--
	2^{7}	1	±1/4 bit	10,000	18	--	1/	1/	-55 to +100	--
Optical	2^{13}	--	1/8 - 192	2,000	11	4.5	50	15G's, 5-2,000 Hz	-55 to +80	3/,4/
	2^{15}	--	1/32 - 768	2,000	18	8.0	50	15G's, 5-2,000 Hz	-55 to +85	3/,4/
	2^{16}	--	1/65 - 536	--	35	--	--	--	-55 to +71	--
	2^{11}	1	±1/4 count	3,000	23	5.0	1/	1/	-20 to +70	--
	1,024	1	1/1,024	3,000	14	1.7	1/	1/	+ 5 to +55	--
	5,000	1	1/5,000	3,000	34	17.0	1/	1/	+ 5 to +55	--
Brush Contact	2^{20}	4,096	1/256	200	11	--	1/	1/	-65 to +125	--
	128,000 ft	16	±50 ft	200	11	--	1/	1/	-65 to +125	--
	2^{19}	4,096	1/524 - 288	200	18	11.9	1/	1/	0 to +85	--
	10^{6}	10,000	1/1,000,000	150	23	21.8	1/	1/	0 to +65	--
	2^{20}	4,096	1/1,048,576	200	18	11.9	2/	2/	0 to +85	3/
	2^{9}	1	1/512	150	23	5.8	60	2/	0 to +85	3/
	1,000	10	1/10,000	50	25	--	1/	1/	-40 to +80	--
	100,000	1,000	1/1,000,000	50	35	--	1/	1/	-40 to +80	--
	3,600	10	1/4 LSD	150	23	9.0	2/	10G's, 20-2,000 Hz	-25 to +100	4/

NOTES:

1/ Variable resistance depending on mounting technique.

2/ In accordance with applicable methods of MIL-STD-202.

3/ Sand and dust resistance in accordance with MIL-STD-810

4/ Humidity resistance in accordance with MIL-STD-810

TABLE XI. Torque and inertia for typical encoders.

Encoder Description								Torque (In.-Oz.)	
Code	Type	Count	Turns	Accuracy	Size	Weight (ounces)	Inertia (Oz.-In^2)	Breakaway	Running
Natural Binary	Brush Contact	2^{19}	4,096	1/524,288	18	11.9	0.07	0.80	0.80
	Brush Contact	2^{20}	4,096	1/1,048,576	18	11.9	0.07	0.80	0.80
	Brush Contact	2^{14}	64	1/16,384	18	8.3	0.07	0.80	0.80
	Brush Contact	2^{7}	1	1/128	18	5.1	0.07	0.80	0.80
	Optical	2^{15}	64	1/32 - 768	18	8.0	0.07	0.50	0.05
	Optical	2^{13}	1	1/8 - 192	11	4.5	0.07	0.10	0.03
Gray	Brush Contact	2^{8}	1	1/256	18	4.5	0.07	0.80	0.80
	Brush Contact	2^{9}	1	1/512	23	5.8	0.16	0.80	0.80
	Brush Contact	2^{10}	1	1/1,024	31	7.5	0.96	1.00	1.00
Binary Coded Decimal	Brush Contact	360,000	3,600	1/360,000	23	0.1716	0.1716	0.75	0.75
	Brush Contact	100,000	1,000	1/1,000,000	35	--	--	3.00	--
	Brush Contact	100,000	10,000	1/1,000,000	35	--	--	0.30	--
	Brush Contact	1,000	1	1/1,000	40	--	--	10.00	--
	Brush Contact	1,000	10	1/1,000	40	--	--	0.10	--
Absolute	Magnetic	2^{13}	64	1/8 - 192	18	--	0.13	0.05	0.05
	Optical	3,600	1	±4' arc	15	4.0	2×10^{-5}	3.00	--
Incremental	Magnetic	2^{7}	1	±1/4 bit	18	--	0.13	0.05	0.05
	Optical	3,600	10	15' arc	23	9.0	0.19	0.80	0.80
	Optical	1,024	1	1/1,024	14	1.8	--	0.15	0.05
	Optical	5,000	1	1/1,500	34	17.0	--	0.40	0.20
	Optical	2,500	1	±4' arc	10	1.5	6×10^{-6} 1/	--	--

NOTE:

1/ Oz.-In/sec^2

TABLE XII. Bearing requirements.

Encoder Resolution and Accuracy	Minimum Required ABEC Rating
Less than 8 bits	3
8 - 10 bits	5
More than 8 bits	7

TABLE XIII. Excess-three to natural binary conversion truth table.

Excess-Three	Decimal	Natural Binary
D C B A		d c b a
0 0 1 1	0	0 0 0 0
0 1 0 0	1	0 0 0 1
0 1 0 1	2	0 0 1 0
0 1 1 0	3	0 0 1 1
0 1 1 1	4	0 1 0 0
1 0 0 1	6	0 1 1 0
1 0 1 0	7	0 1 1 1
1 0 1 1	8	1 0 0 0
1 1 0 0	9	1 0 0 1

TABLE XIV. Set-Reset selector circuit truth table.

Q_{t-1}	Inputs		output
	Set	Reset	Q_t
0	1	0	1
1	1	0	1
0	1	1	1
1	1	1	1
0	0	1	0
1	0	1	0
0	0	0	0
1	0	0	1

TABLE XV. Set-Reset selector circuit control functions.

Encoder		
Control A	Select E	Function
1	1	Follow
0	1	Store
0	0	Inhibit
1	0	Inhibit

TABLE XVI. Set-Reset inter-disc or inter-belt selector circuit - truth table.

Inputs			Outputs	
Q_{t-1}	R	S	Q_t $(C_{lag}{}^2)$	$\overline{Q_t}$ $(C_{lead}{}^2)$
0	1	0	0	1
1	1	0	0	1
0	0	1	1	0
1	0	1	1	0
0	0	0	0	1
1	0	0	1	0
1	1	1	Not Permitted	
0	1	1		

TABLE XVII. Sequence of operations for high reliability logic system.

Mode	Circuit Operation	Results
FOLLOW	A = True B = False X Select = True System Latch = False	Signals on the system data bus follow X encoder. Signals on the system data bus indicate instantaneous position of X encoder. Non-selected encoders are not commutating current.
LATCH SELECTOR BIT	A = True B = True X Select = True System Latch = True	2^0 bit remains True if momentary sensor conduction occurs. 1/
STORE SELECTOR BIT	A = False B = True X Select = True	System is in STORE mode.
LATCH ALL BITS	A = False B = True X Select = True System Latch = True	Any momentary True detected at the input to the latching register stored as a True signal. 1/
STORE ALL BITS	A = False B = False X Select = False System Latch = True	Reduces effect of noise, cable capacitance, and current commutation.

NOTE:

1/ Interval (latch) should be 100 microseconds or longer, but should not exceed 0.10 of the minimum quantum time.

TABLE XVIII. Typical operating specifications for an external driver circuit.

Operating Parameters	Minimum	Typical Value Nominal	Maximum
Supply Voltage	18.0 V	22.0 (±0.5) V	26.0 V
Supply Current	40 mA		100 mA
Input Power	0.9 watts	----	2.6 watts
Operating Temperature Change	-20°C		+60°C
Input Voltage	8.0 V	10.0 V	12.0 V
Input Current	----	----	----
Signal Outputs	----	----	----
Logical "1"	19.5 v	20.5 V	21.5 V
Logical "0"	0.0 v	0.0 V	0.1 V
Output Switching Speed	----	----	l.O psec 1/
Current Available	1 mA to 2 mA per bit as determined by external encoder load resistance.		

NOTE:

1/ 10-90 percent.

TABLE XIX. Encoder test procedures.

	Mechanical Checks
Step	Procedure
1	Measure mechanical dimensions.
2	Measure clearances.
3	Check shaft end play.
4	check shaft radial play.
5	Check shaft runout.
6	check shaft torque (breakaway and running).
7	Check shaft perpendicularity.

	Electrical Tests
Step	Procedure
1	Using oscillograph, monitor encoder output count. Analyze plot to ensure counts are in proper sequence, and that transitions occur within tolerance. 1/
2	For unit distance coded units, monitor output of unit distance bit with oscillograph. Analyze plot to ensure minimum quantum bit width is within tolerance. 1/
3	Analyze plot to ensure that edge noise is within tolerance.
4	Using autocorrelator, test for encoder dropout at maximum rated speed.

NOTE:

1/ Use marker generator timing tracks (transition marks) as a reference for verifying proper output count and that unit distance bit output is correct.

TABLE XX. Counting in other number systems.

Decimal	Duodecimal	Octal	Binary
0	0	0	0
1	1	1	1
2	2	2	10
3	3	3	11
4	4	4	100
5	5	5	101
6	6	6	110
7	7	7	111
8	8	10	1000
9	9	11	1001
10	A	12	1010
11	B	13	1011
12	10	14	1100
13	11	15	1101
14	12	16	1110
15	13	17	1111
16	14	20	10000
17	15	21	10001

NOTE:

1/ Digit limitation within a given numbering system.

TABLE XXI. Four-digit natural binary code and corresponding decimal system numbers.

Decimal Number	Natural Binary					Decimal Number	Natural Binary					
	Base 1/	23	22	21	20		Base 1/	(24)	23	22	21	20
	Weight	8	4	2	1		Weight	(16)	8	4	2	1
0		0	0	0	0	9			1	0	0	1
1		0	0	0	1	10			1	0	1	0
2		0	0	1	0	11			1	0	1	1
3		0	0	1	1	12			1	1	0	0
4		0	1	0	0	13			1	1	0	1
5		0	1	0	1	14			1	0	0	1
6		0	1	1	0	15			1	1	1	1
7		0	1	1	1	16		1	0	0	0	0
8		1	0	0	0							

NOTE :

1/ Exponent.

TABLE XXII. Incremental code and corresponding decimal system numbers.

Decimal Number	Incremental Number	Decimal Number	Incremental Number
0	00	6	10
1	01	7	11
2	10	8	00
3	11	9	01
4	00	10	10
5	01	11	11

TABLE XXIII. 8-4-2-1 binary coded decimal.

Decimal Digit	8-4-2-1 Binary Coded Decimal
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001

TABLE XXIV. Binary coded octal system.

Decimal Number	Binary Coded Octal Number
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

TABLE XXV. 7-4-2-1 binary coded decimal.

Decimal Digit	7-4-2-1 Binary Coded Decimal
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	1000
8	1001
9	1010

TABLE XXVI. Two-out-of-seven code.

Decimal Number	Quibinary Code		Standard Biquinary Coded Decimal		Odd-Even Biquinary Coded Decimal	
	Qui	Bi	Bi	Qui		
0	00001	01	01	00001	00001	0
1	00001	10	01	00010	00001	1
2	00010	01	01	00100	00010	0
3	00010	10	01	01000	00010	1
4	00100	01	01	10000	00100	0
5	00100	10	10	00001	00100	1
6	01000	01	10	00010	01000	0
7	01000	10	10	00100	01000	1
8	10000	01	10	01000	10000	0
9	10000	10	10	10000	10000	1

TABLE XXVII. Two-out-of-five code.

Decimal Number	Two-Out-of-Five Code
0	00000
1	00011
2	00101
3	00110
4	01001
5	01010
6	01100
7	10001
8	10010
9	10100

TABLE XXVIII. Five binary number systems.

Decimal	Natural Binary	Cyclic Binary (Gray Code)	Excess 3	Binary	Cyclic Binary Decimal
0	0000	0000	0011	0000 0000	0000 0000
1	0001	0001	0100	0000 0001	0000 0001
2	0010	0011	0101	0000 0010	0000 0011
3	0011	0010	0110	0000 0011	0000 0010
4	0100	0110	0111	0000 0100	0000 0110
5	0101	0111	1000	0000 0101	0000 0111
6	0110	0101	1001	0000 0110	0000 0101
7	0111	0100	1010	0000 0111	0000 0100
8	1000	1100	1011	0000 1000	0000 1100
9	1001	1101	1100	0000 1001	0000 1000
10	1010	1111	1101	0001 0000	0001 1000
11	1011	1110	1110	0001 0001	0001 1001
12	1100	1010	1111	0001 0010	0001 1011
13	1101	1011	10000	0001 0011	0001 1010
14	1110	1001	10001	0001 0100	0001 1110
15	1111	1000	10010	0001 0101	0001 1111
16	10000	11000	10011	0001 0110	0001 1101
17	10001	11001	10100	0001 0111	0001 1100

TABLE XXIX. Gray code.

Decimal Number	Gray Binary Code	Decimal Number	Gray Binary Code
0	0000	8	1100
1	0001	9	1101
2	0011	10	1111
3	0010	11	1110
4	0110	12	1010
5	0111	13	1011
6	0101	14	1001
7	0100	15	1000

TABLE XXX. Nonweighted, nonreflected cyclic code.

Cyclic Decimal Number	Decimal Number	Cyclic Code	
		Tens	Units
0	0	1000	1000
1	1	1000	1100
2	2	1000	0100
3	3	1000	0110
4	4	1000	0010
5	5	1000	0011
6	6	1000	0111
7	7	1000	0101
8	8	1000	1101
9	9	1000	1001
Cyclic Decimal Reflection Point			
19	10	1100	1001
18	11	1100	1101
17	12	1100	0101
16	13	1100	0111
15	14	1100	0011
14	15	1100	0010
13	16	1100	0110
12	17	1100	0100
11	18	1100	1100
10	19	1100	1000

TABLE XXXI. Excess-3 code and derivation.

Decimal Number	Excess-3 Digits	8-4-2-1 BCD	Excess-3 BCD
0	Excess 1	0000	----
1	Excess 2	0001	----
2	Excess 3	0010	----
3	0	0011	0011
4	1	0100	0100
5	2	0101	0101
6	3	0110	0110
7	4	0111	0111
8	5	1000	1000
9	6	1001	1001
10	7	1010	1010
11	8	1011	1011
12	9	1100	1100

TABLE XXXII. Partial ICAO Code, selected sequential values.

Decoded Gray	Actual Altitude (Feet)	Reflected Cyclic Gray Bits								Nonreflected Cyclic Bits			
		D2	D4	A1	A2	A4	B1	B2	B4	C1	C2	C4	100's
0	-1200	0	0	0	0	0	0	0	0	0	0	1	8
	-1100	0	0	0	0	0	0	0	0	0	1	1	9
	-1000	0	0	0	0	0	0	0	0	0	1	0	0
	- 900	0	0	0	0	0	0	0	0	1	1	0	1
	- 800	0	0	0	0	0	0	0	0	1	0	0	2
1	- 750								↓				
	- 700	0	0	0	0	0	0	0	1	1	0	0	3
	- 600	0	0	0	0	0	0	0	1	1	1	0	4
	- 500	0	0	0	0	0	0	0	1	0	1	0	5
	- 400	0	0	0	0	0	0	0	1	0	1	1	6
	- 300	0	0	0	0	0	0	0	1	0	0	1	7
2	- 250							↓					
	- 200	0	0	0	0	0	0	1	1	0	0	1	8
	- 100	0	0	0	0	0	0	1	1	0	1	1	9
	000	0	0	0	0	0	0	1	1	0	1	0	0
	100	0	0	0	0	0	0	1	1	1	1	0	1
	200	0	0	0	0	0	0	1	1	1	0	0	2
3	250								↓				
	300	0	0	0	0	0	0	1	0	1	0	0	3
	400	0	0	0	0	0	0	1	0	1	1	0	4
	500	0	0	0	0	0	0	1	0	0	1	0	5
	600	0	0	0	0	0	0	1	0	0	1	1	6

TABLE XXXII. Partial ICAO Code, selected sequential values - Continued.

Decoded Gray	Actual Altitude (Feet)	Reflected Cyclic Gray Bits								Nonreflected Cyclic Bits			
		D2	D4	A1	A2	A4	B1	B2	B4	C1	C2	C4	100's
3 (Cont'd)	700	0	0	0	0	0	0	1	0	0	0	1	7
	750						↓						
4	800	0	0	0	0	0	1	1	0	0	0	1	8
	900	0	0	0	0	0	1	1	0	0	1	1	9
	1000	0	0	0	0	0	1	1	0	0	1	0	0
	1100	0	0	0	0	0	1	1	0	1	1	0	1
	1200	0	0	0	0	0	1	1	0	1	0	0	2
5	1250								↓				
	1300	0	0	0	0	0	1	1	1	1	0	0	3
	1400	0	0	0	0	0	1	1	1	1	1	0	4
	1500	0	0	0	0	0	1	1	1	0	1	0	5
	1600	0	0	0	0	0	1	1	1	0	1	1	6
	1700	0	0	0	0	0	1	1	1	0	0	1	7
6	1750							↓					
	1800	0	0	0	0	0	1	0	1	0	0	1	8
	1900	0	0	0	0	0	1	0	1	0	1	1	9
	2000	0	0	0	0	0	1	0	1	0	1	0	0
	2100	0	0	0	0	0	1	0	1	1	1	0	1
	2200	0	0	0	0	0	1	0	1	1	0	0	2
7	2250								↓				
	2300	0	0	0	0	0	1	0	0	1	0	0	3
	2400	0	0	0	0	0	1	0	0	1	1	0	4

TABLE XXXII. Partial ICAO Code, selected sequential values - Continued.

Decoded Gray	Actual Altitude (Feet)	Reflected Cyclic Gray Bits								Nonreflected Cyclic Bits			
		D2	D4	A1	A2	A4	B1	B2	B4	C1	C2	C4	100's
7 (Cont'd)	2500	0	0	0	0	0	1	0	0	0	1	0	5
	2600	0	0	0	0	0	1	0	0	0	1	1	6
	2700	0	0	0	0	0	1	0	0	0	0	1	7
8	2750					↓							
	2800	0	0	0	0	1	1	0	0	0	0	1	8
	2900	0	0	0	0	1	1	0	0	0	1	1	9
	3000	0	0	0	0	1	1	0	0	0	1	0	0
	3100	0	0	0	0	1	1	0	0	1	1	0	1
	3200	0	0	0	0	1	1	0	0	1	0	0	2
9	3250								↓				
	3300	0	0	0	0	1	1	0	1	1	0	0	3
	3400	0	0	0	0	1	1	0	1	1	1	0	4
	3500	0	0	0	0	1	1	0	1	0	1	0	5
	3600	0	0	0	0	1	1	0	1	0	1	1	6
	3700	0	0	0	0	1	1	0	1	0	0	1	7
10	3750							↓					
	3800	0	0	0	0	1	1	1	1	0	0	1	8
	3900	0	0	0	0	1	1	1	1	0	1	1	9
	4000	0	0	0	0	1	1	1	1	0	1	0	0

TABLE XXXIII. <u>ICAO Code,forbidden bit changes--Bits C1, C2, and C4.</u>

	100-Foot Increments	Bits		
		C1	**C2**	**C4**
	0	0	1	0
	1	1	1	0
Forbidden Change	2	1	0	0
	3	1	0	0
	4	1	1	0
	5	0	1	0
	6	0	1	1
Forbidden Change	7	0	0	1
	8	0	0	1
	9	0	1	1

TABLE XXXIV. Gray-coded Excess-3 Binary Coded Decimal.

Arabic Digit	Excess-3 Digit	Gray-Coded Excess-3 BCD	
		Tens	Units
0	3	0010	0010
1	4	0010	0110
2	5	0010	0111
3	6	0010	0101
4	7	0010	0100
5	8	0010	1100
6	9	0010	1101
7	10	0010	1111
8	11	0010	1110
9	12	0010	1010
10	13	0110	1010
11	14	0110	0110
12	15	0110	0111
13	16	0110	0101
14	17	0110	1100
15	18	0110	0100
16	19	0110	0101
17	20	0110	0111
18	21	0110	0110
19	22	0110	0010
20	23	0111	0010

TABLE XXXV. Two-out-of-five coding.

Arabic Digit	Two-Out-of-Five Code 7 4 2 1 P
0	1 1 0 0 0
1	0 0 0 1 1
2	0 0 1 0 1
3	0 0 1 1 0
4	0 1 0 0 1
5	0 1 0 1 0
6	0 1 1 0 0
7	1 0 0 0 1
8	1 0 0 1 0
9	1 0 1 0 0

TABLE XXXVI. Unit distance code for minutes or seconds with one-bit complement.

Arabic Numeral	Code
0	001
1	011
2	010
3	110
4	111
5	101

TABLE XXXVII. Unit distance code of 0-23 hours.

Hours	Hours + 4	Binary Code 16 8 4 2 1	Gray Code
0	4	0 0 1 0 0	0 0 1 1 0
1	5	0 0 1 0 1	0 0 1 1 1
2	6	0 0 1 1 0	0 0 1 0 1
3	7	0 0 1 1 1	0 0 1 0 0
4	8	0 1 0 0 0	0 1 1 0 0
5	9	0 1 0 0 1	0 1 1 0 1
6	10	0 1 0 1 0	0 1 1 1 1
7	11	0 1 0 1 1	0 1 1 1 0
8	12	0 1 1 0 0	0 1 0 1 0
9	13	0 1 1 0 1	0 1 0 1 1
10	14	0 1 1 1 0	0 1 0 0 1
11	15	0 1 1 1 1	0 1 0 0 0
12	16	1 0 0 0 0	1 1 0 0 0
13	17	1 0 0 0 1	1 1 0 0 1
14	18	1 0 0 1 0	1 1 0 1 1
15	19	1 0 0 1 1	1 1 0 1 0
16	20	1 0 1 0 0	1 1 1 1 0
17	21	1 0 1 0 1	1 1 1 1 1
18	22	1 0 1 1 0	1 1 1 0 1
19	23	1 0 1 1 1	1 1 1 0 0
20	24	1 1 0 0 0	1 0 1 0 0
21	25	1 1 0 0 1	1 0 1 0 1
22	26	1 1 0 1 0	1 0 1 1 1
23	27	1 1 0 1 1	1 0 1 1 0

TABLE XXXVIII. Boolean logic summary.

Theorem	**Formula**
Commutative Law	$a + b = b + a$
	$ab = ba$
Associative Law	$(a + b) + c = a + (b + c)$
	$(ab)\ c = a\ (bc)$
Distributive Law	$a\ (b + c) = ab + ac$
	$(a + b)\ (a + c) = a + bc$
De Morgans Theorem	$\bar{a} + \bar{b} = (\overline{ab})$
	$(\overline{ab}) = (\bar{a} + \bar{b})$
Rules of Inference:	
Modus Ponens	$p \longrightarrow q$
	p
	$\therefore \quad q$
Modus Tollens	$p \longrightarrow q$
	q
	$\therefore \quad p$
Symbols:	
$\longrightarrow$	implies
~ or	not
•	and
+	or
v	inclusive or
=	equals, therefore, then

TABLE XXXIX. Truth table for AND logic equation.

Condition Number	Variables			Result
	Switch A	Switch B	Lamp C	
1	0	0	0	1
2	1	0	0	1
3	0	1	0	1
4	1	1	0	0
5	0	0	1	0
6	1	0	1	0
7	0	1	0	0
8	1	1	1	1

TABLE XL. Set-Reset truth table.

Past LSB	Selector Inputs		Present Output (Corrected)
	Set	Reset	
0	1	0	1
1	1	0	1
0	1	1	1
1	1	1	1
0	0	1	0
1	0	1	0
→ 0	0	0	0 ←
→ 1	0	0	1 ←

TABLE XLI. Encoder specification checklist.

Parameter	Options
OUTPUT CODE	8-4-2-1 Binary Coded Decimal Natural Binary Gray Binary Cyclic Decimal ICAO (MOA-Gillham) Excess-3 Binary Coded Decimal Excess-3 Gray Code Biquinary Two-Out-of-Five Binary Coded Decimal 4-2-2-1 Binary Incremental: With Zero Index Reference Without Zero Index Reference
ANTI-AMBIGUITY LOGIC	Window Code Unit Distance Code V-Scan Self-Selecting V-Scan M-Scan U-Scan Self-Selecting U-Scan
OUTPUT NOTATION	Linear Degrees, Minutes Hours, Minutes Sine-Cosine Square Root Functions Other Trigonometric Functions Longitude Latitude Thermocouple EMF - Temperature Curve Copper Constantan Iron Constantan Chromel Alumel Other Thermocouples Resistance Bulb Temperature Curve Dewcell Temperature Curve Other Non-Linear Range
MECHANICAL APPLICATIONS	Maximum Reading Speed in rpm Maximum Slewing Speed in rpm Average Reading Speed in rpm Average Slewing Speed in rpm Life: (1) Revolutions (2) Hours Maximum Allowable Torque in Oz.-In. : (1) Breakaway (2) Running Maximum Allowable Momment of Inertia in Gm-Cm^2

TABLE XLI. Encoder specification checklist - Continued.

Parameter	Options
MECHANICAL APPLICATIONS (Continued)	Transition Accuracy Required: (1) Percent of One Count, (2) Angle in Degree of Arc Shaft Diameter Shaft Length Shaft Type: Solid Hollow Plain, Slot, Spline, or Pinion Through Shaft Mounting Size: Size 11 Synchro Mount Size 15 Synchro Mount Size 18 Synchro Mount Size 23 Synchro Mount Size 31 Synchro Mount Size 35 Synchro Mount Case Diameter: Size 11 1.062 in. Size 15 1.500 in. Size 18 1.750 in. Size 23 2.250 in. Size 31 3.062 in. Size 35 3.500 in. Size 40 4.000 in. Size 55 5.500 in. Size 65 6.500 in. Case Length in Inches (less shaft) Maximum Tolerable Weight Output Connection: Pigtail Leads Cable with Connector Integral Connector Terminals
ELECTRICAL APPLICATIONS	Maximum Load Voltage per Digit Maximum Load Current per digit Load Impedance in Ohms Load: Pure Resistance Reactance Drive Circuits: External to Encoder Internal Diodes: External Internal Polarity

TABLE XLI. Encoder specification checklist - Continued.

Parameter	Options
ENVIRONMENT	Shock in G’s Vibration Range in Hertz Operating Temperature Range Humidity Application: Ground Military Airborne Laboratory Industrial Space
GENERAL CHARACTERISTICS	Rotation for Ascending Count: (1) Clockwise (2) Counterclockwise Number of Counts for Full Scale Output Number of Turns for Full Scale Output (Multi-Turn) Number of Counts per Turn (Multi-Turn) Degree of Rotation for Full Count (Single Turn) Single or Double Zero Count and Sign of output
MISCELLANEOUS	Auxiliary External Circuits: Filter Buffer Drive Circuits Translator Storage Circuits outputs: Serial Parallel Both

TABLE XLII. Size comparison of encoders for various configurations.

Logic		V-Scan			Gray Code or U-Scan 2-Bit Select			U-Scan 1-Bit Select			Window Scan			Cyclic			
Bits	Counts	Turns	Bits/ Rev	Dia. (in.)	Turns	Bits/ Rev	Dia. (in.)	Turns	Bits/ Rev	Dia. (in.)	Turns	Bits/ Rev	Dia. (in.)	Turns	Bits/ Rev	Dia. (in.)	No. of Stages
7	128	--	--	--	--	--	--	--	--	0.8	--	--	--	--	--	--	Single
8	256	--	--	1.1	--	--	0.8	--	--	1.4	--	--	1.8	--	--	--	Single
9	512	--	--	2.3	--	--	1.4	--	--	2.3	--	--	3.0	--	--	--	Single
10	1,024	--	--	3.5	--	--	2.3	--	--	--	--	--	4.5	--	--	--	Single
11	2,048	--	--	5.5	--	--	4.5	--	--	--	--	--	--	--	--	--	Single
12	4,096	--	--	--	--	--	6.3	--	--	--	--	--	--	--	--	--	Single
9	512	2	8	1.1	2	8	1.1	2	8	1.8	--	--	--	--	--	--	2
10	1,024	4	8	1.1	4	8	1.1	4	8	1.8	--	--	--	--	--	--	2
11	2,048	8	8	1.1	8	8	1.1	8	8	1.8	--	--	--	--	--	--	2
12	4,096	16	8	1.1	16	8	1.1	16	8	1.8	--	--	--	--	--	--	2
13	8,192	32	8	1.1	32	8	1.1	32	8	1.8	--	--	--	--	--	--	2
14	16,384	32	9	2.3	32	9	1.8	64	8	1.8	--	--	--	--	--	--	2
15	32,768	64	9	2.3	64	9	1.8	--	--	--	--	--	--	--	--	--	2
16	65,536	64	10	3.5	64	10	3.5	--	--	--	--	--	--	--	--	--	2
17	131,072	128	10	3.5	128	10	3.5	--	--	--	--	--	--	--	--	--	2
14	16,384	64	8	1.1	64	8	1.1	--	--	--	--	--	--	--	--	--	3
15	32,768	128	8	1.1	128	8	1.1	128	8	1.8	--	--	--	--	--	--	3
16	65,536	256	8	1.1	256	8	1.1	256	8	1.8	--	--	--	--	--	--	3
17	131,072	512	8	1.1	512	8	1.1	512	8	1.8	--	--	--	--	--	--	3
18	262,144	1,024	8	1.1	1,024	8	1.1	1,024	8	1.8	--	--	--	--	--	--	3
19	524,288	1,024	9	2.3	512	10	2.3	2,048	8	1.8	--	--	--	--	--	--	3
20	1,048,576	2,048	9	2.3	1,024	10	2.3	4,096	8	1.8	--	--	--	--	--	--	3
21	2,097,152	4,096	9	2.3	2,048	10	2.3	--	--	--	--	--	--	--	--	--	3
9	±100	--	--	--	--	--	--	--	--	--	--	--	--	1	200	1.1	Single
12	1,000	--	--	--	--	--	--	--	--	--	--	--	--	1	1,000	2.3	Single
13	±1,000	--	--	--	--	--	--	--	--	--	--	--	--	1	2,000	4.5	Single
12	1,000	--	--	--	--	--	--	--	--	--	--	--	--	10	100	1.1	2
16	10,000	--	--	--	--	--	--	--	--	--	--	--	--	50	200	1.8	2
20	100,000	--	--	--	--	--	--	--	--	--	--	--	--	100	1,000	3.5	2
16	10,000	--	--	--	--	--	--	--	--	--	--	--	--	100	100	1.1	3
20	100,000	--	--	--	--	--	--	--	--	--	--	--	--	200	500	1.8	3
24	1,000,000	--	--	--	--	--	--	--	--	--	--	--	--	200	5,000	2.3	3

TABLE XLIII. Lubricant and bearing material considerations for high temperature operation.

Temperature (°F)	Consideration
275°	Temperature limit for phenolic retainer.
300°	Limit for 52100 steel and synthetic diester and mineral oil lubricants.
350°	Limit for untreated 400C stainless steel and silicon lubricants.
400°	Limit for available high temperature grease of suitable characteristics.
600°	Limit for heat-treated 440C stainless steel.
Above 600° to 1500°	Gas lubrication and special metals self-generating natural oxided lubrication and possibly molybdenum disulphide to 750°F.

TABLE XLIV. Lubricant and bearing material considerations for high vacuum operation.

Pressure (mm Hg)	Consideration or Solution
10^{-5}	Normal bearing and lubricant limit for full life.
10^{-7}	Mineral oil lubricants below 300°F or synthetic diester oil. Reduce internal pressure by shielded bearings. Use phenolic retainers.
10^{-9}	Use silicon grease.
10^{-11}	Experimental areas include metallic film lubrication.

TABLE XLV. Lubricant and bearing maerial considerations for nuclear radiation environments.

Radiation Level (Roentgens)	Applicable Lubricant
106	Use silicon greases and fluids to 8 x 10^6 roentgens and metal retainers above 5 x 10^6 roentgens.
107	Use diester oils to 5 x 10^7 roentgens or mineral oils below 8 x 10^7 roentgens.
108	Use of special greases possible to 3 x 10^8 roentgens.

TABLE XLVI. Lubricant considerations for low temperature operations.

Temperature (°F)	Applicable Lubricant
To 0°	Use mineral oils down to 0 degrees.
To -45°	Use polyalkylene glycol.
To -55°	Use silicon fluids or grease.
To -100°	Use diester oil.

TABLE XLVII. Designation of encoder type.

Type	Designation
Capacitive	C
Eddy Current	E
Magnetic	M
Contact	K
Optical (lamp)	L
Optical (LED)	S
Other	W

TABLE XLVIII. Designation of code and scan.

Code and Scan	Designation
Natural Binary, Line-Scan	A
Natural Binary, U-Scan	B
Natural Binary, V-Scan	C
Natural Binary, M-Scan	N
Reflected (Cyclic) Binary (Gray Code) Line Scan	D
Reflected (Cyclic) Binary (Gray Code) Lead-Lag	P
Binary Coded Decimal, Line-Scan	E
Binary Coded Decimal, U-Scan	F
Binary Coded Decimal, V-Scan	G
Binary Coded Decimal, M-Scan	M
Decimal, Line-Scan	H
Incremental (With Zero Reference)	J
Incremental (Without Zero Reference)	K
Altitude Reporting (ICAO)	U
Other	W

TABLE XLIX. Designation of logic and output.

Logic	output	Designation
External	Parallel	J
External	Serial	K
Internal	Parallel	L
Internal	Serial	M

TABLE L. Designation of function.

Function	Designation
Linear	R
Sine-Cosine	S
Tangent	T
Exponential	X
Logarithmic	Z
Other	W

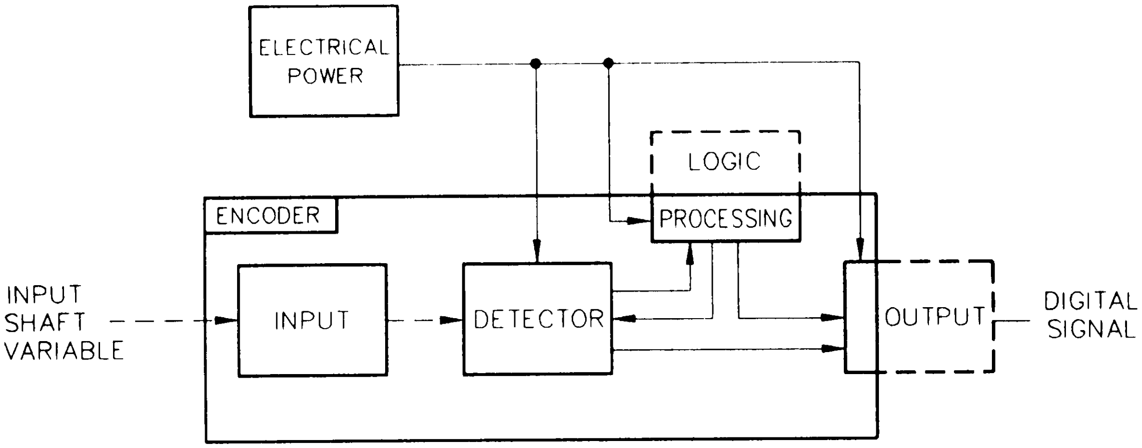


FIGURE 1. Digital shaft encoder system - basic functional block diagram.

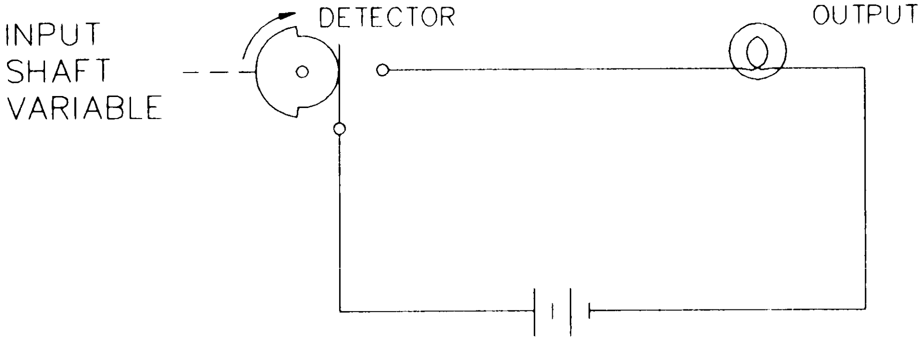


FIGURE 2. One-bit digital encoder.

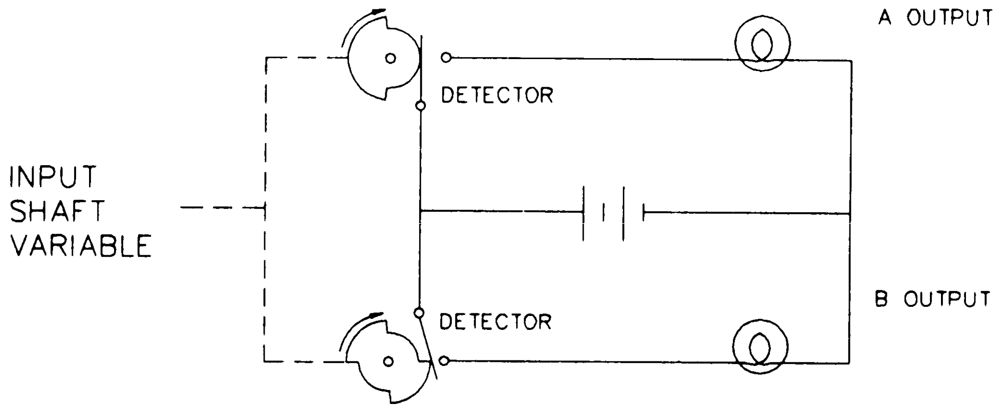


FIGURE 3. Two-bit cam switch encoder (A).

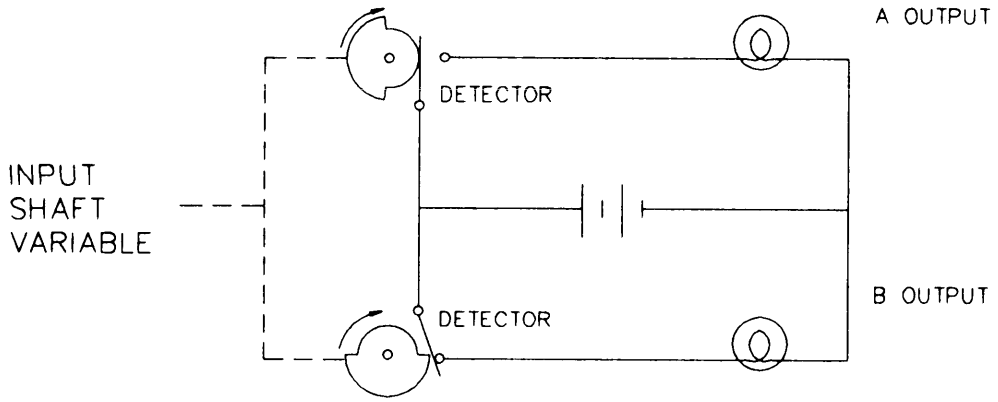


FIGURE 4. Two-bit cam switch encoder (B).

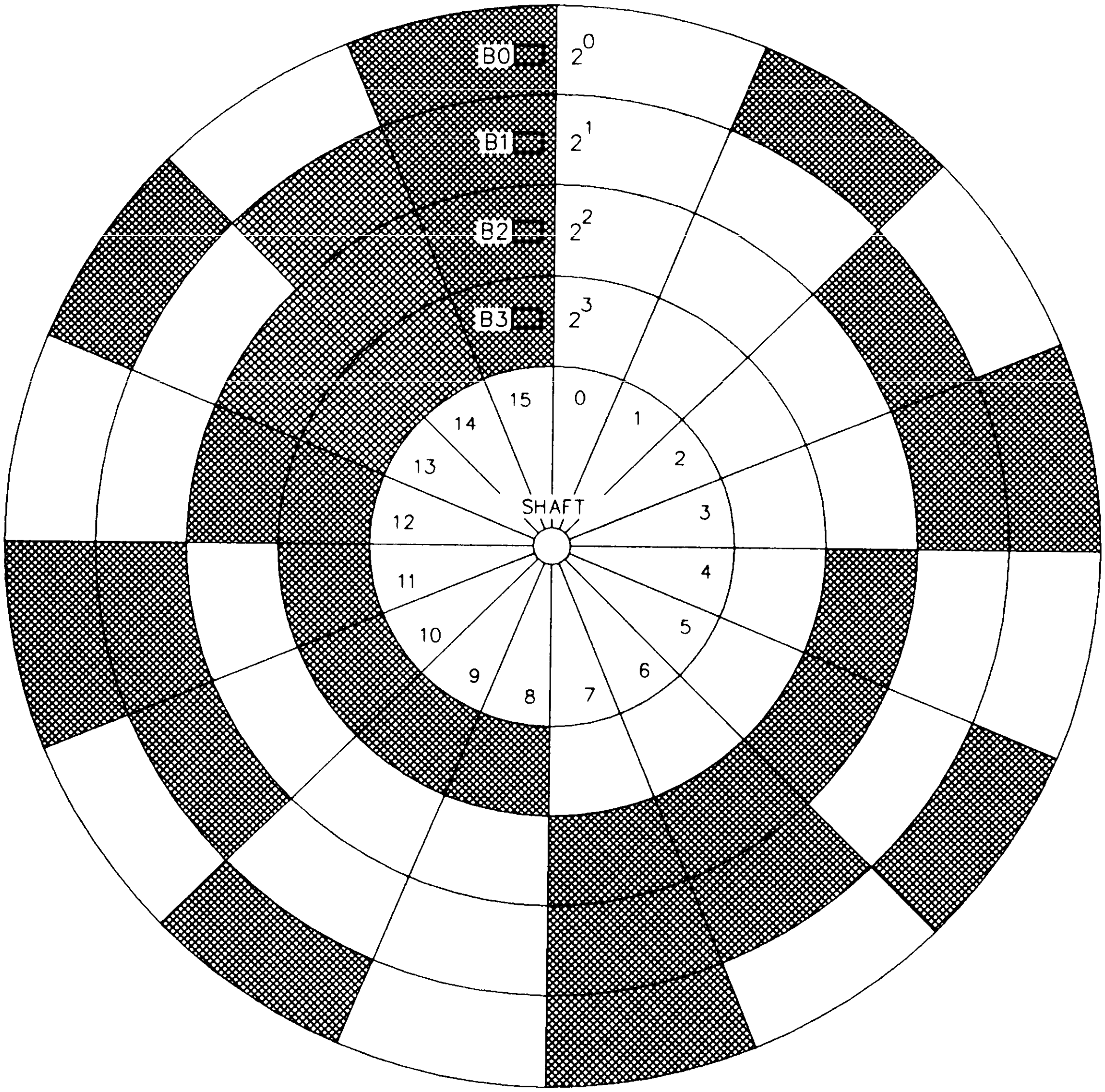


FIGURE 5. Encoder disc pattern with natural binary code.

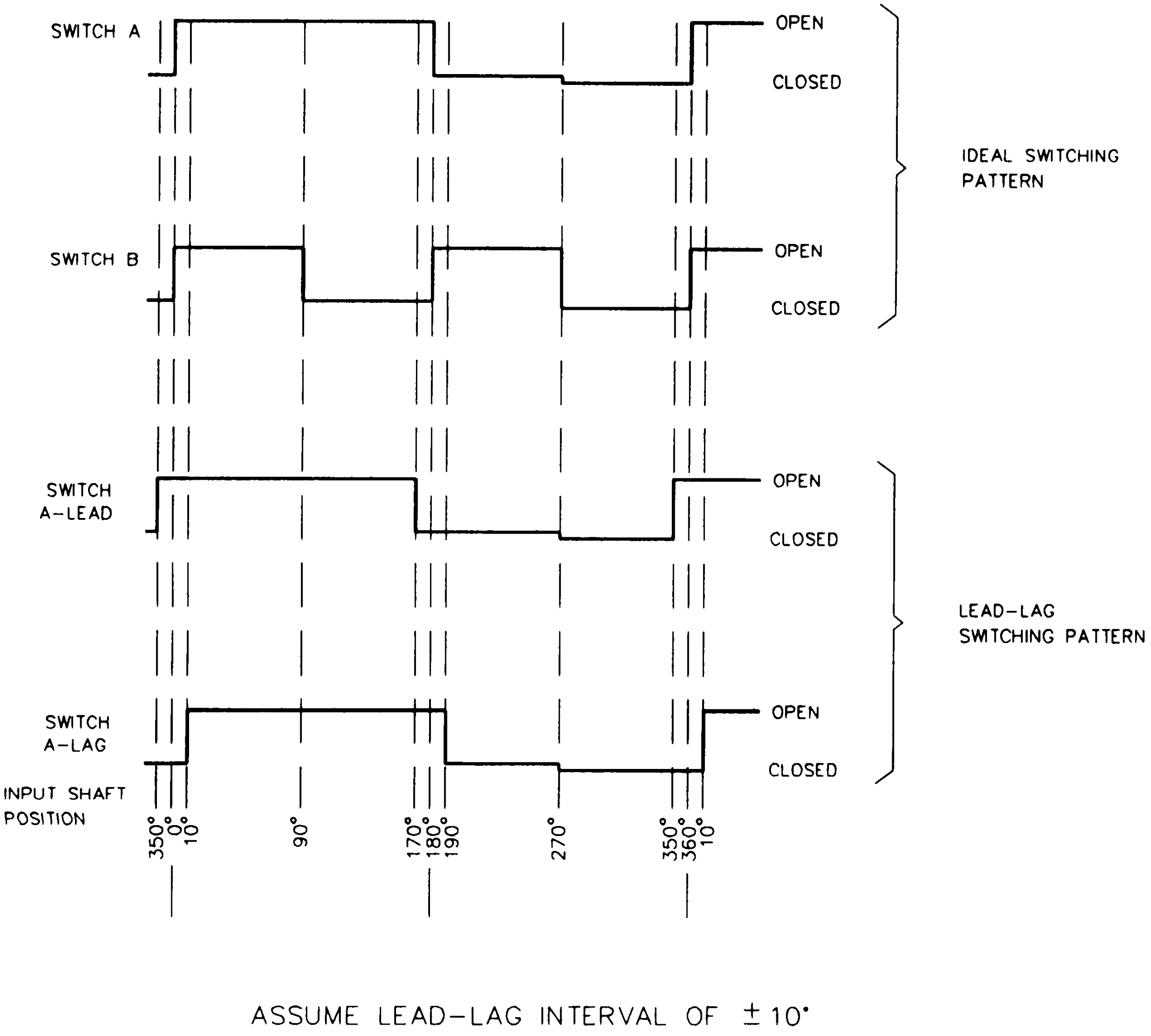


FIGURE 6. Timing diagram for two-bit lead-lag switching.

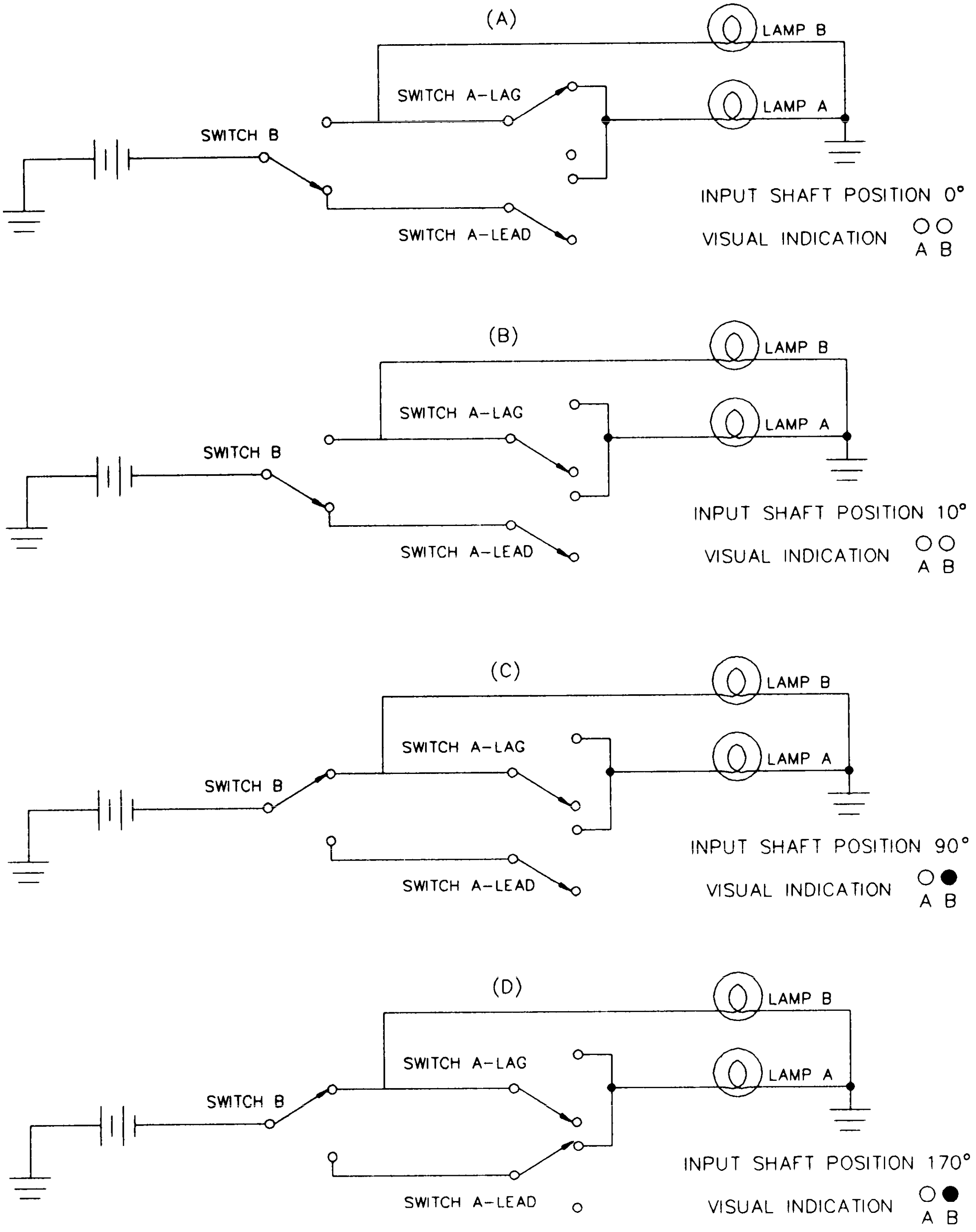


FIGURE 7. Switching sequence for two-bit cam switch encoder with anti-ambiguitv logic.

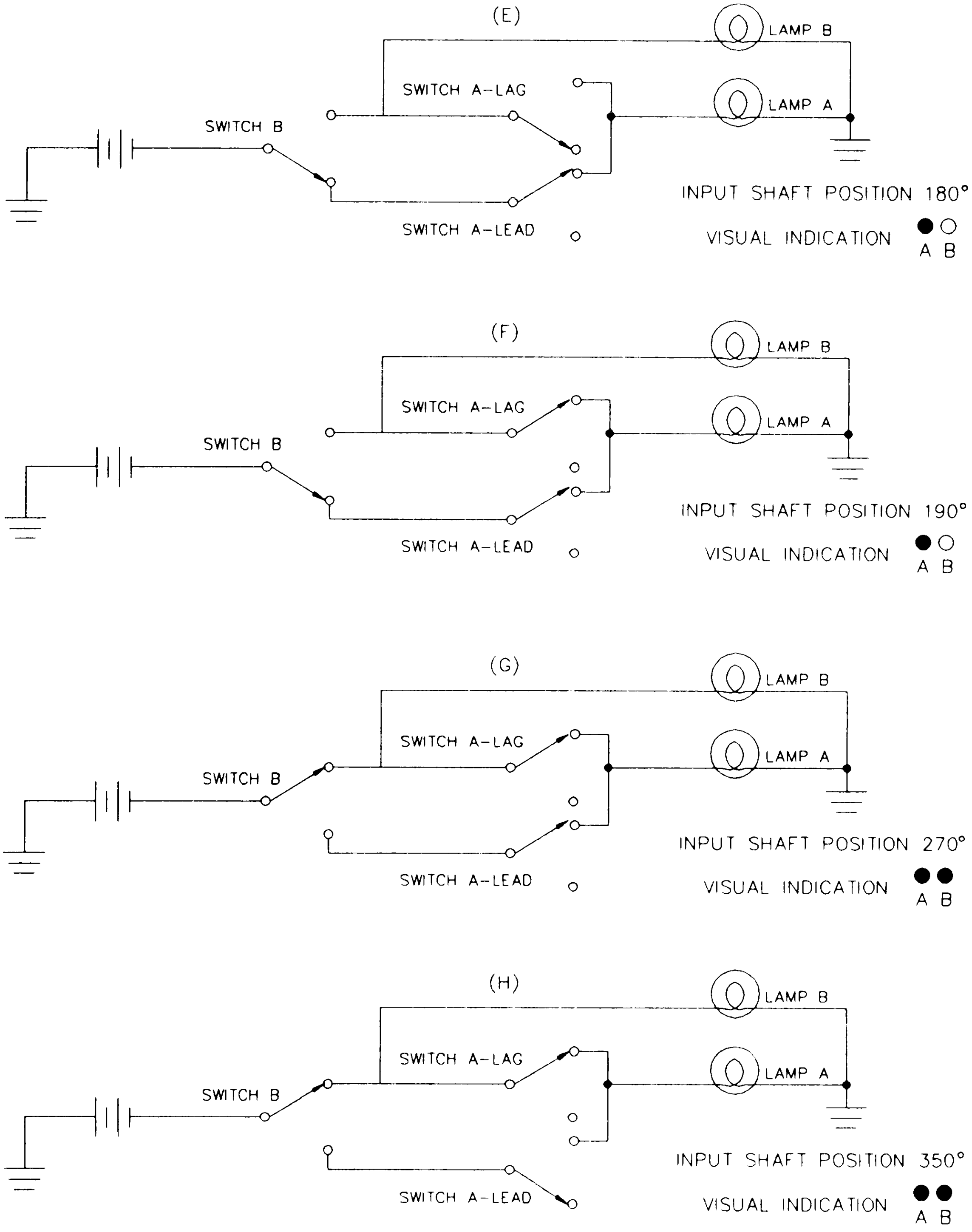


FIGURE 7. Switching sequence for two-bit cam switch encoder with anti-ambiguity logic - Continued.

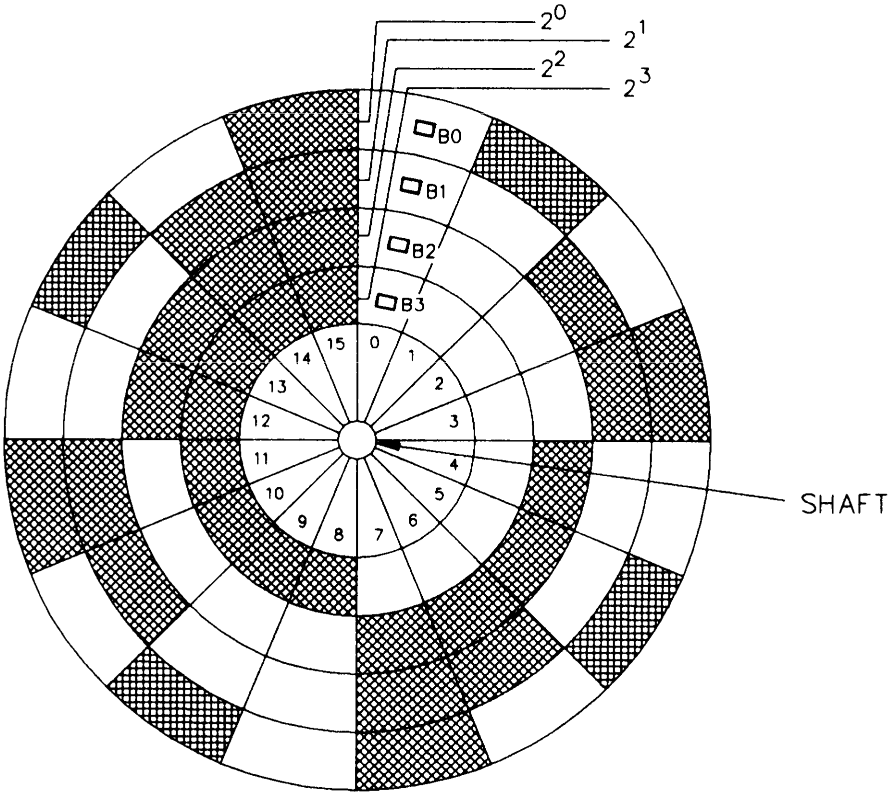


FIGURE 8. Contact encoder disc.

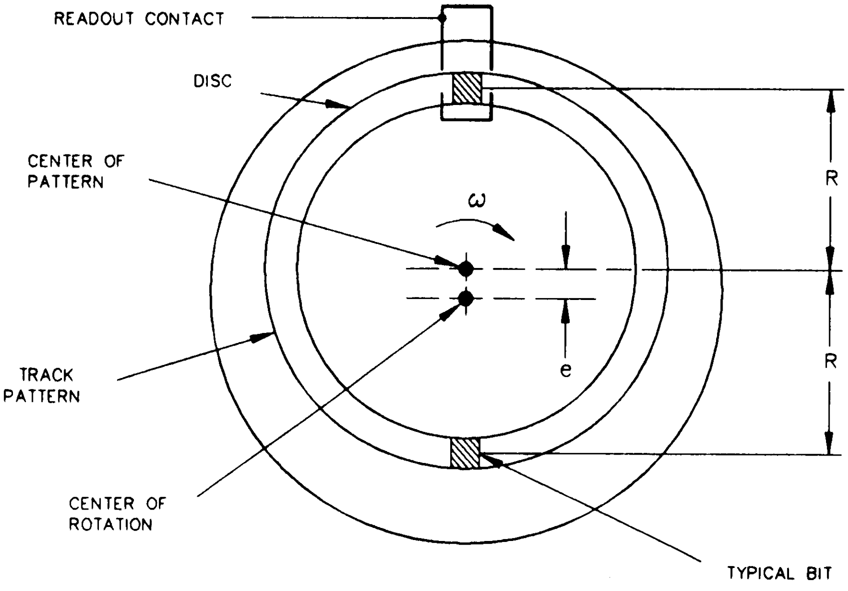


FIGURE 9. Pattern eccentricity in an encoder disc.

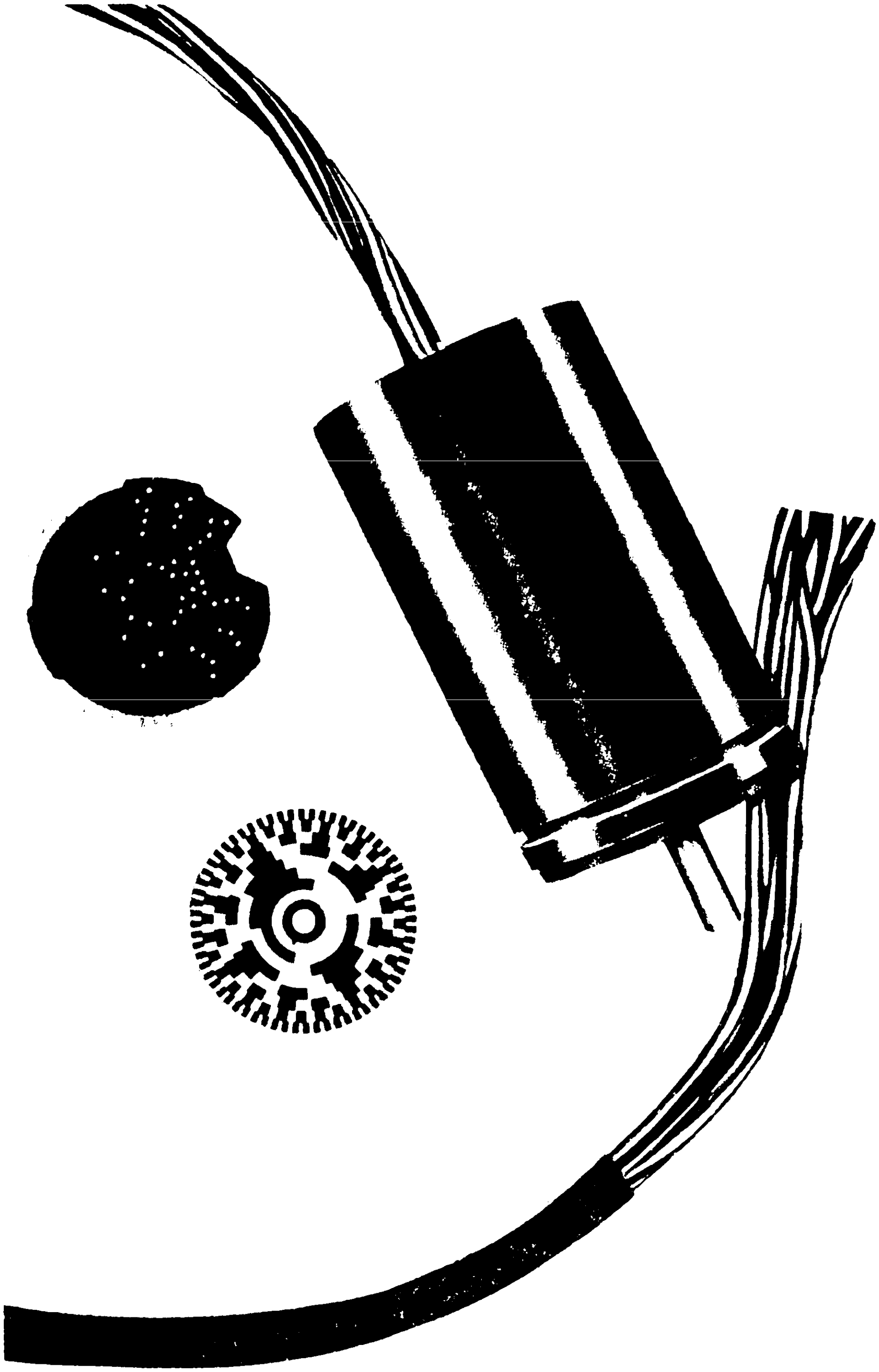
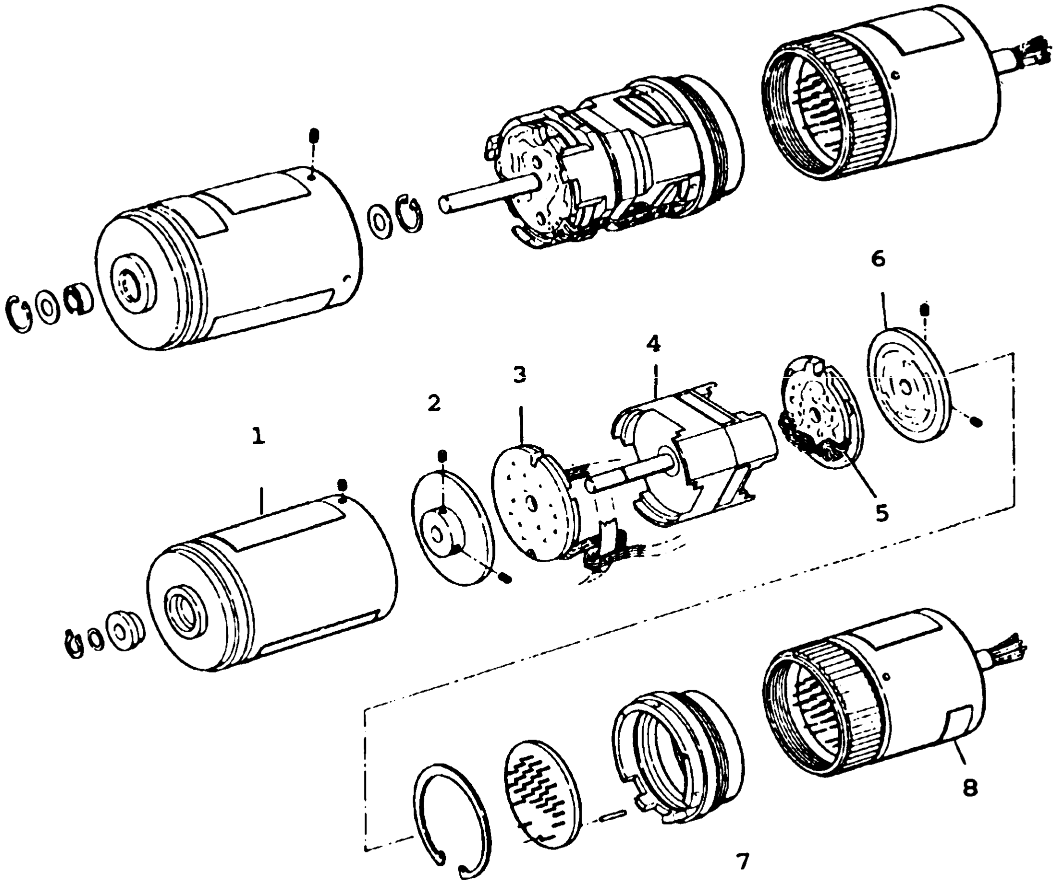


FIGURE 10. Pin contact encoder.



1. Outer Case
2. High Speed commutator Disc
3. High Speed Pin Cage
4. Gear Box
5. Low Speed Pin Cage
6. Low Speed Disc
7. Connector Shell
8. Connector Mounted Decoding Package

FIGURE 11. Pin encoder, cutaway view.

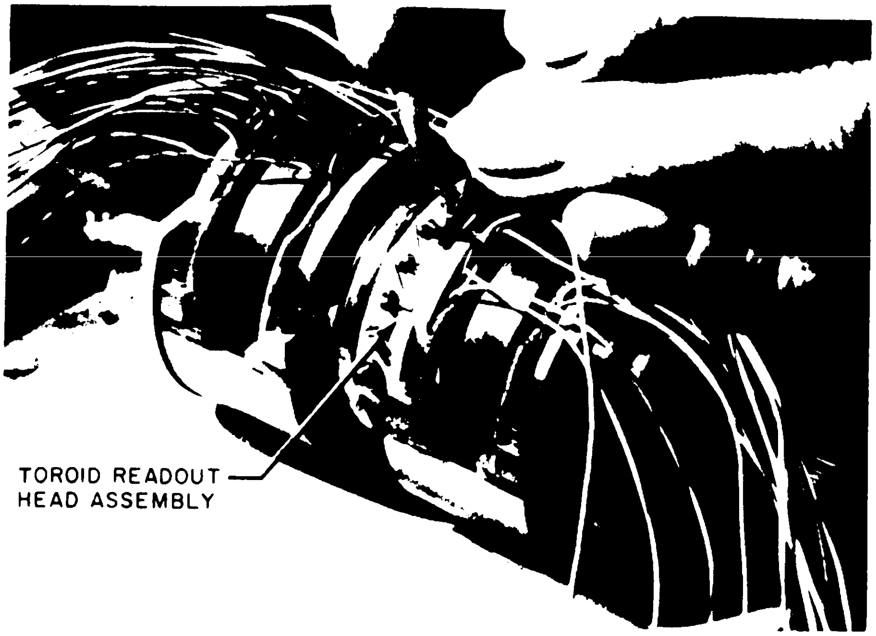


FIGURE 12. Magnetic encoder,, cutaway view.

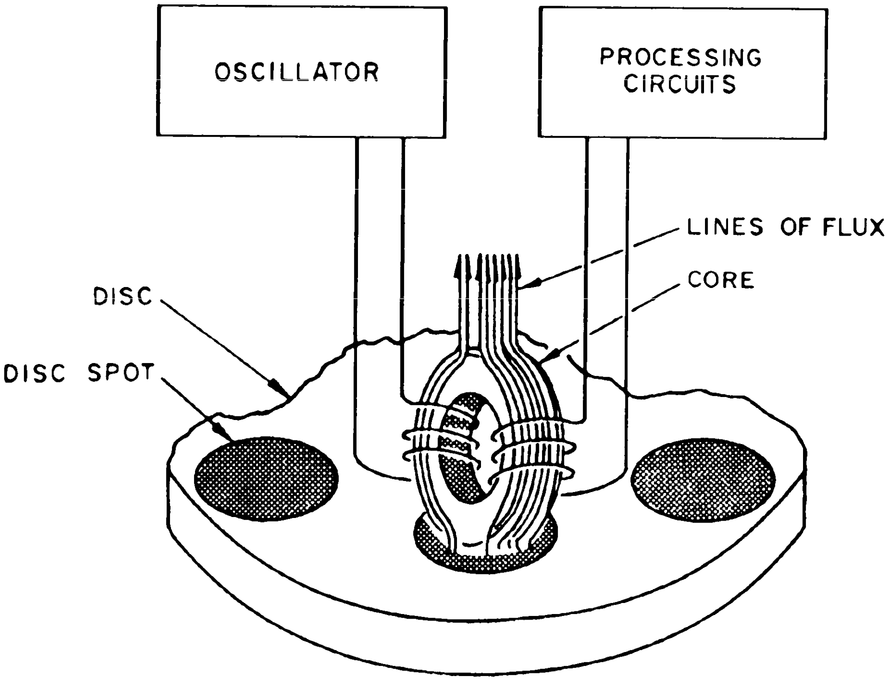


FIGURE 13. Magnetic encoder operation.

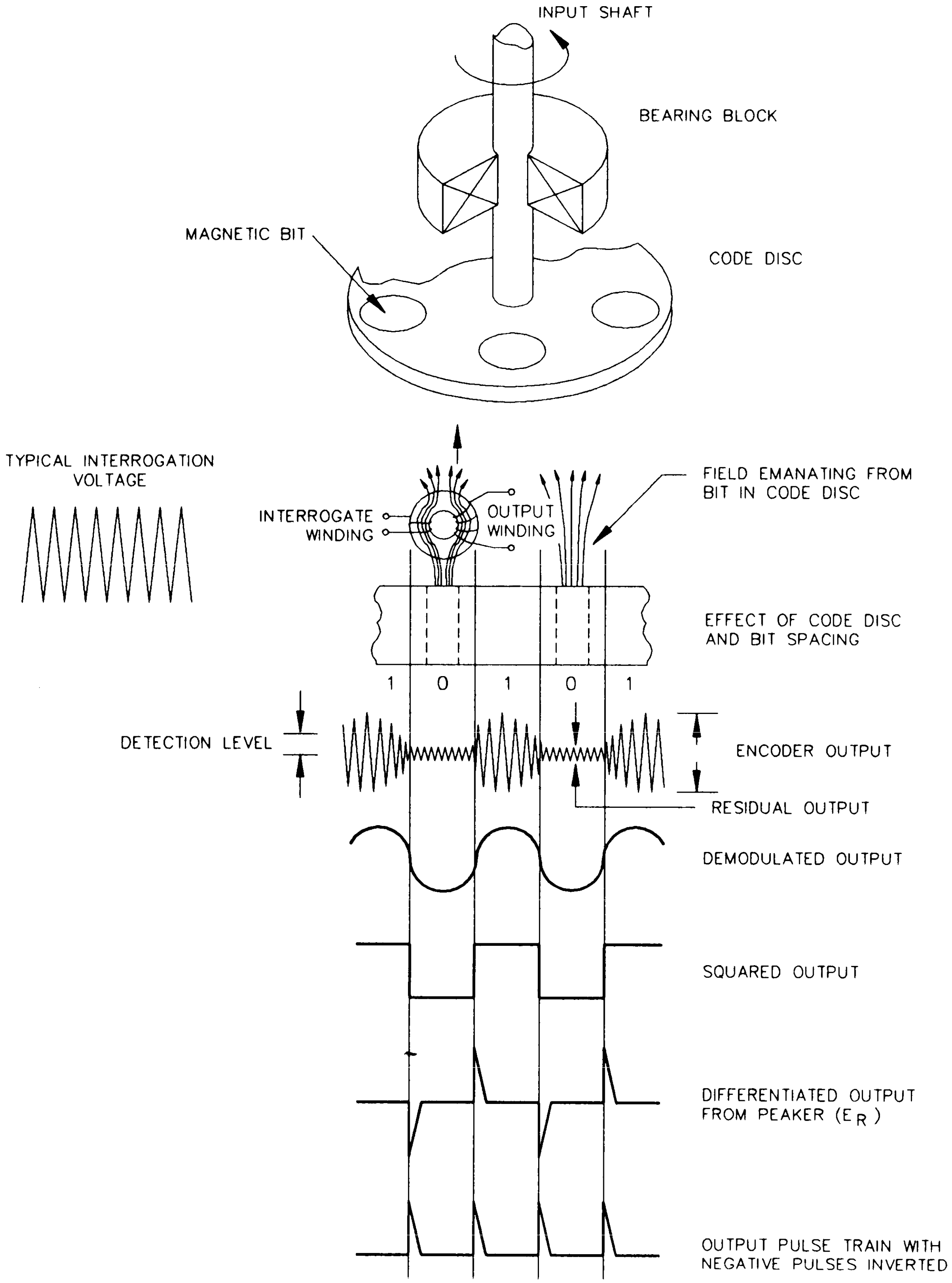


FIGURE 14. Typical magnetic encoding.

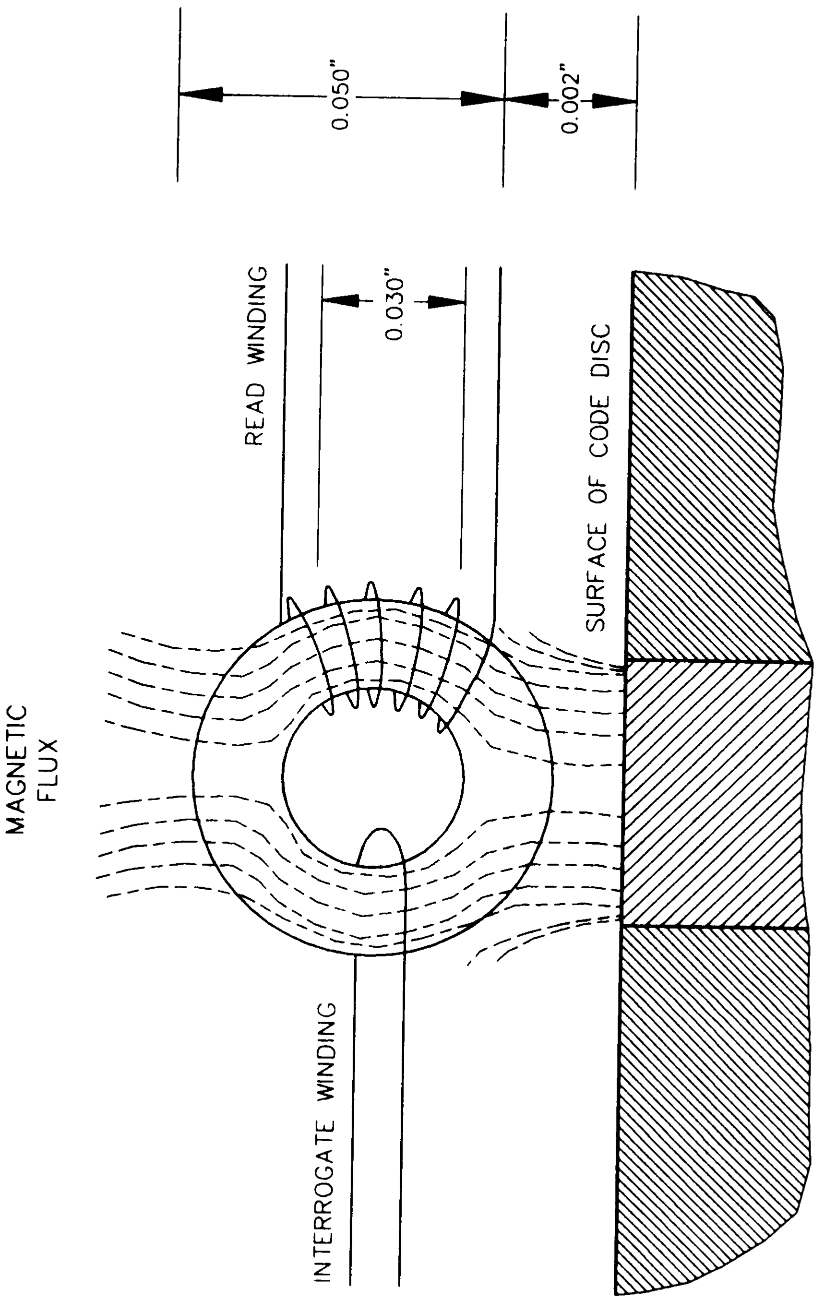


FIGURE 15. Toroidal magnetic head.

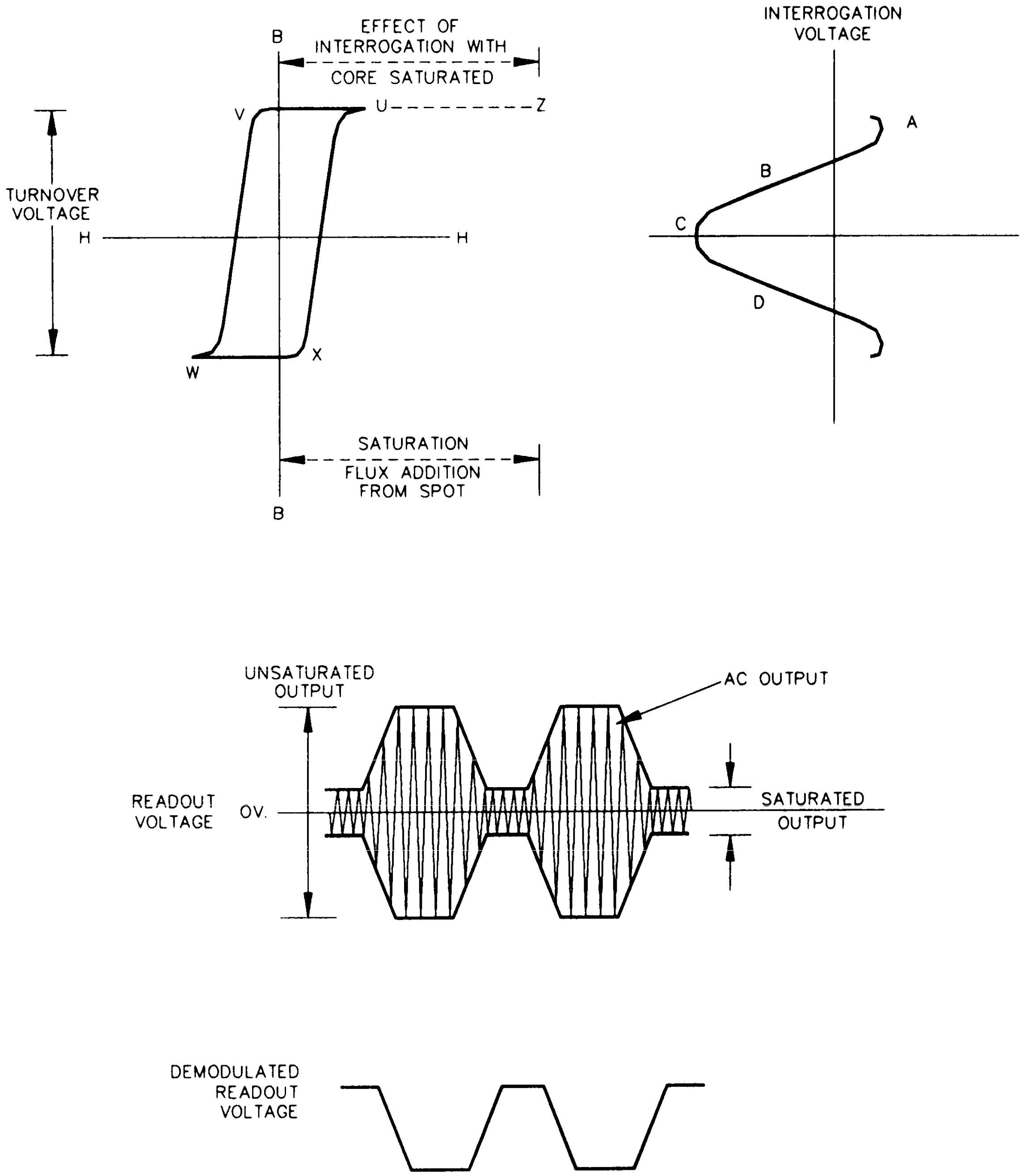


FIGURE 16. Magnetic head, hysteresis loop and readout voltage.

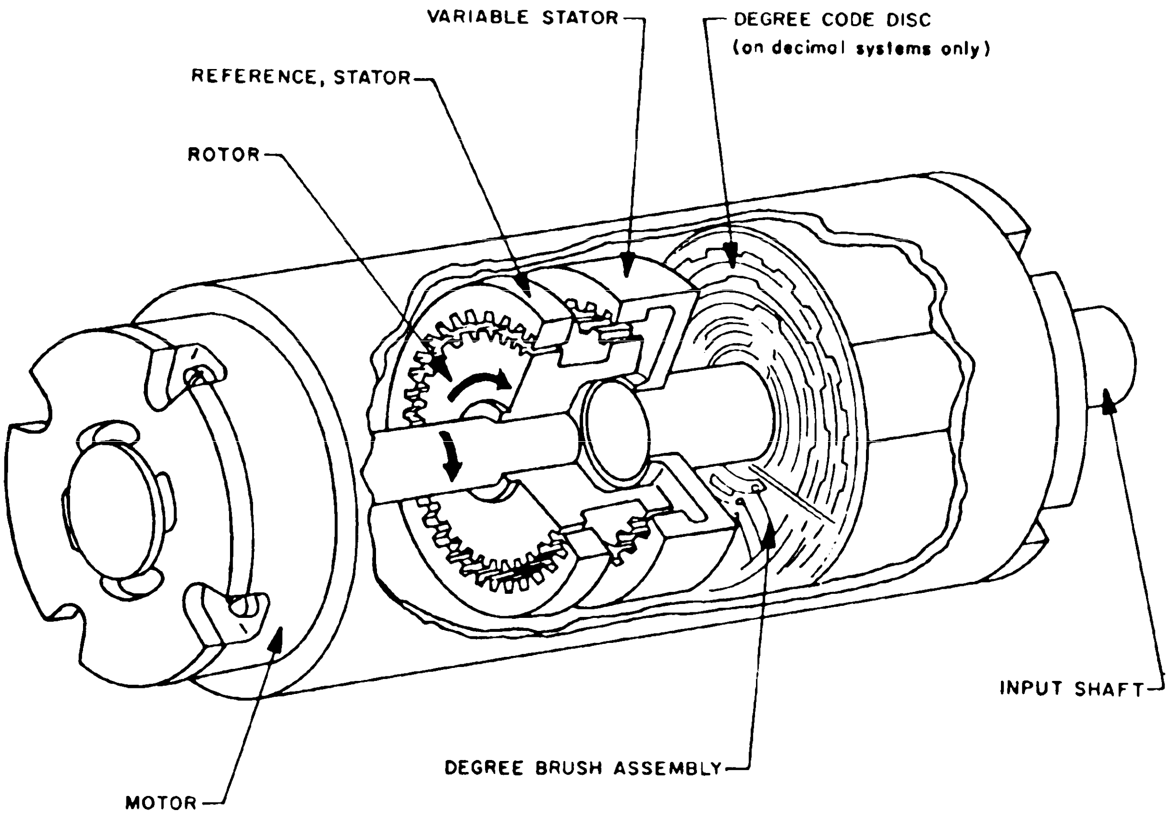
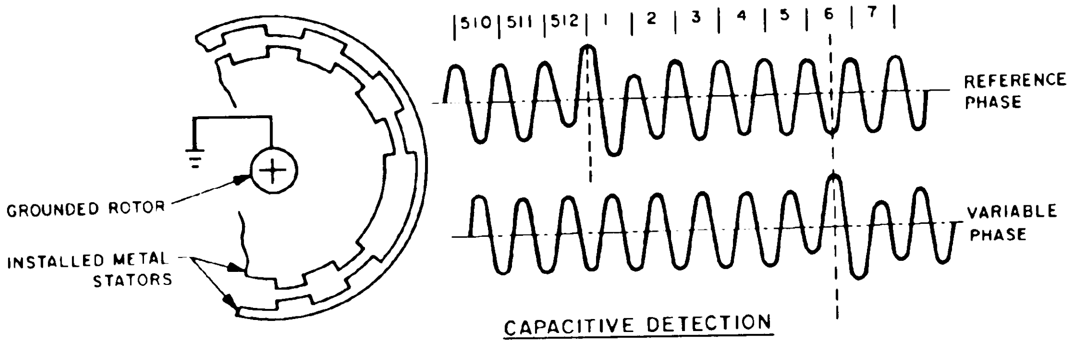


FIGURE 17. Capacitive encoder, cutaway view.



CAPACITIVE DETECTION

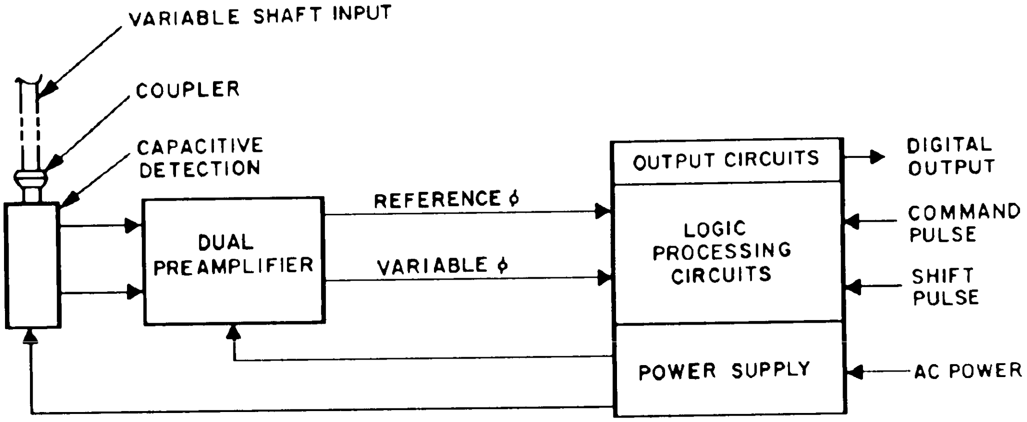


FIGURE 18. Capacitive encoder.

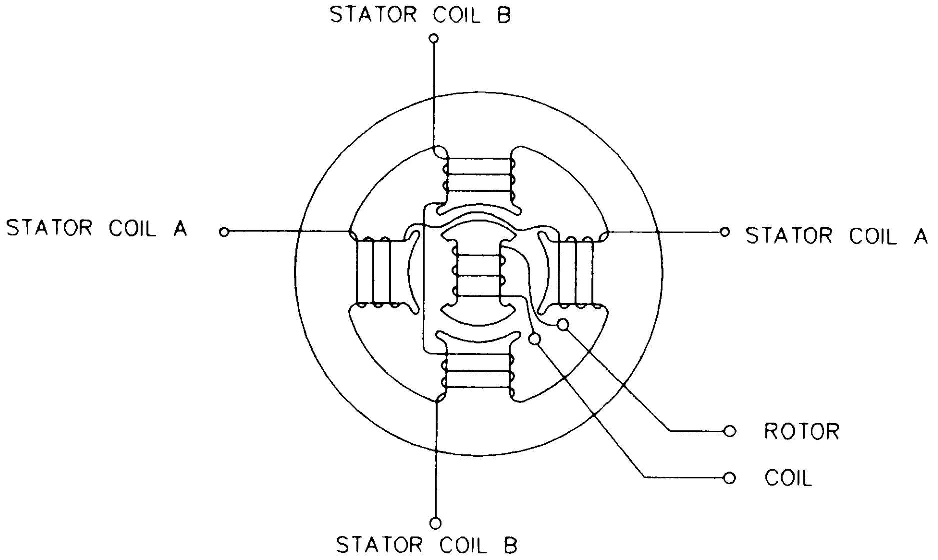


FIGURE 19. Inductive encoder symbolized by resolver windings.

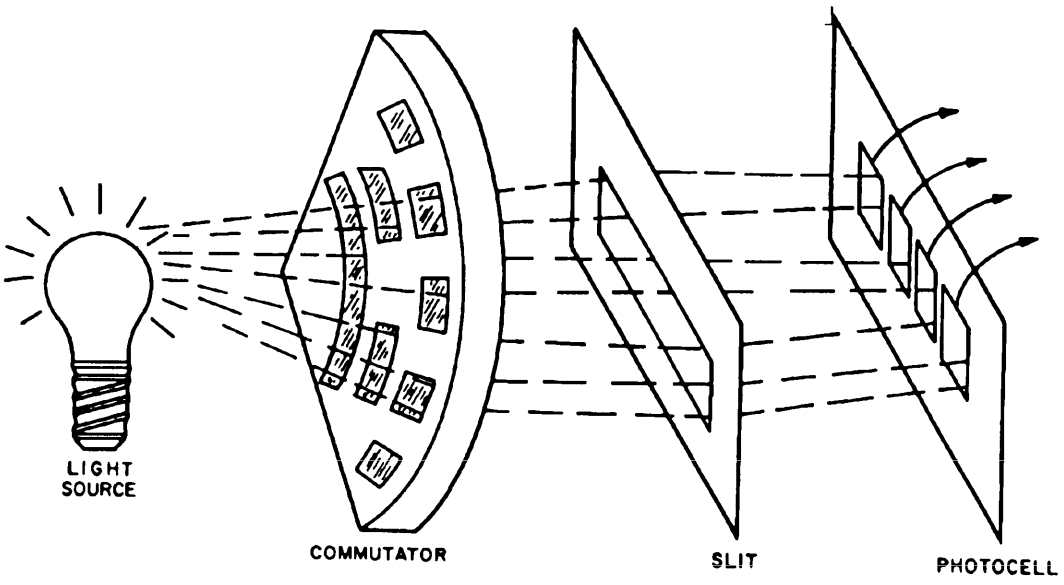


FIGURE 20. Optical encoder operation.

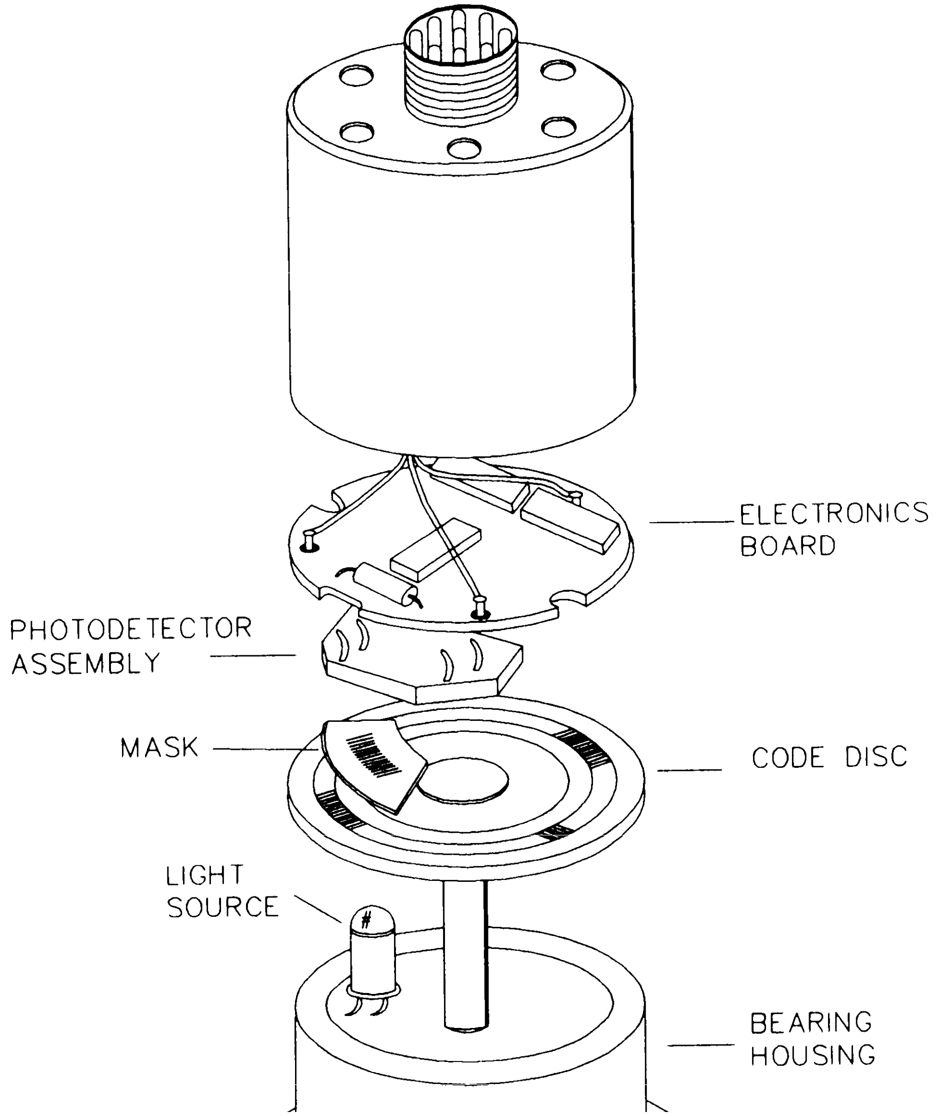


FIGURE 21. Typical optical encoder.

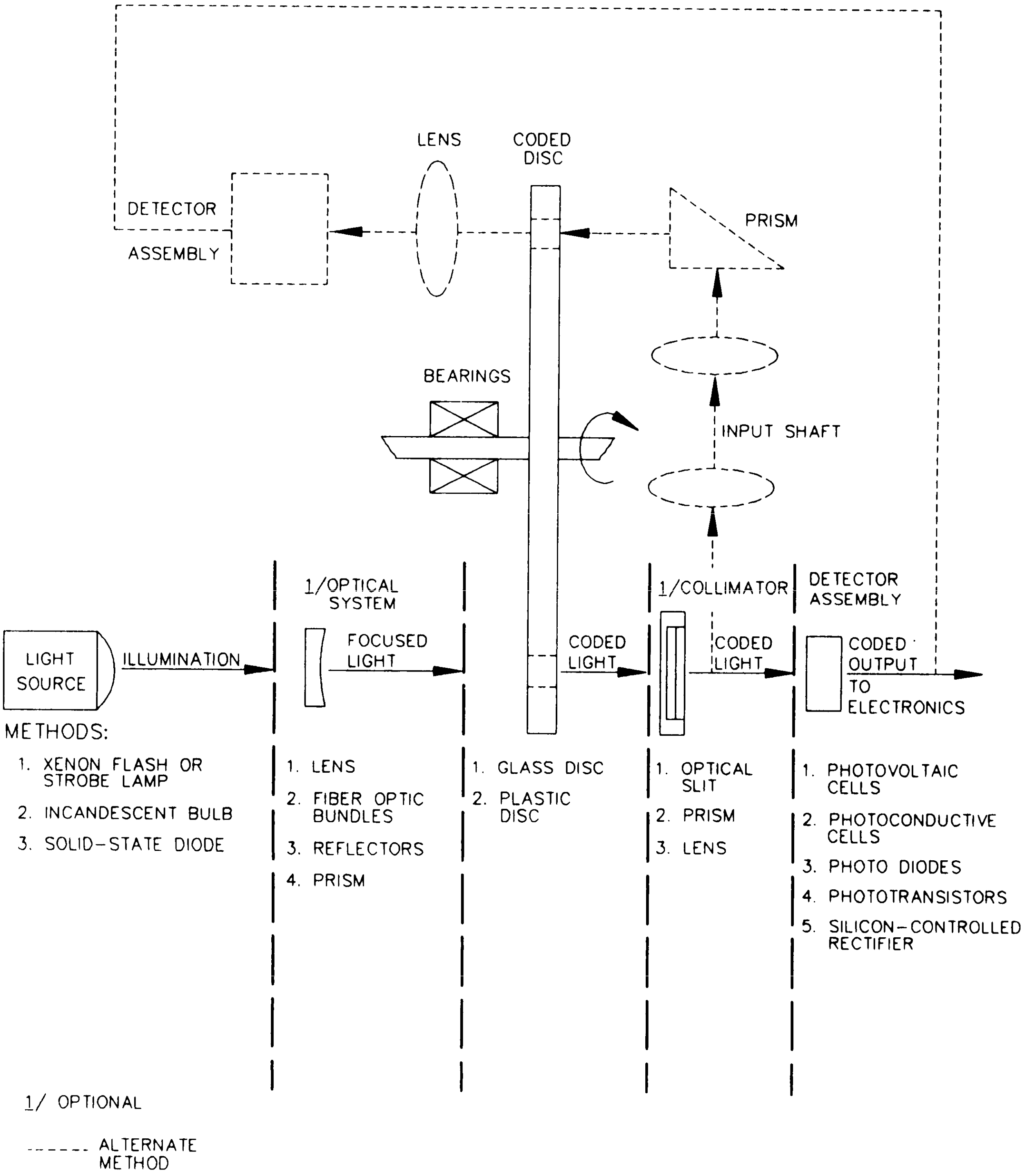


FIGURE 22. Optical sensing, functional diagram.

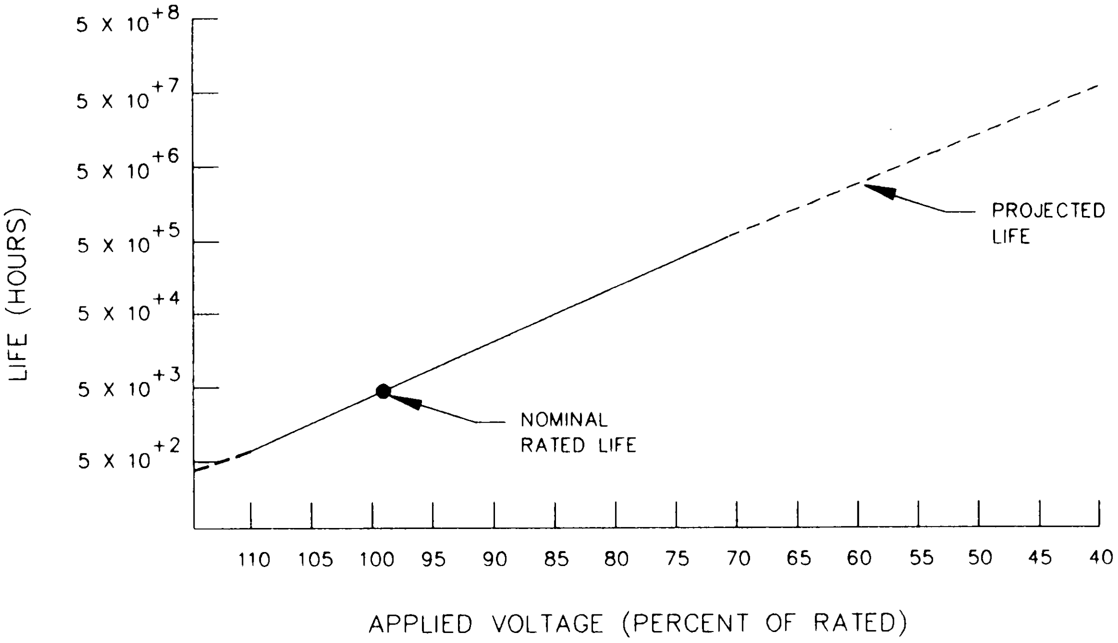


FIGURE 23. Incandescent bulb life, voltage curve.

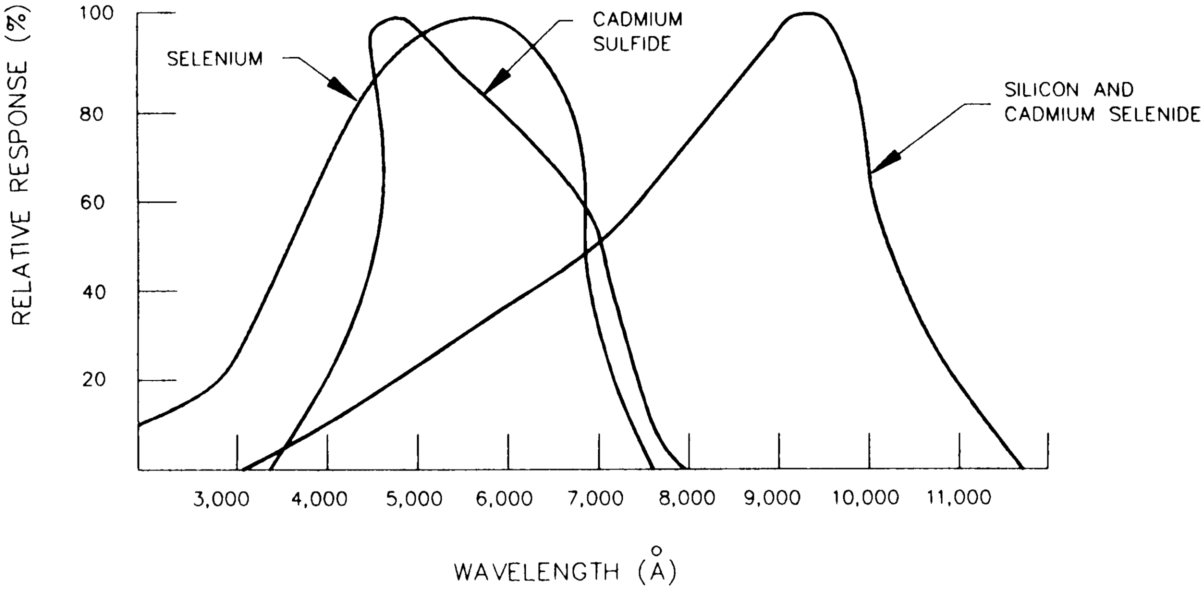


FIGURE 24. Generalized response of various light sensitive materials.

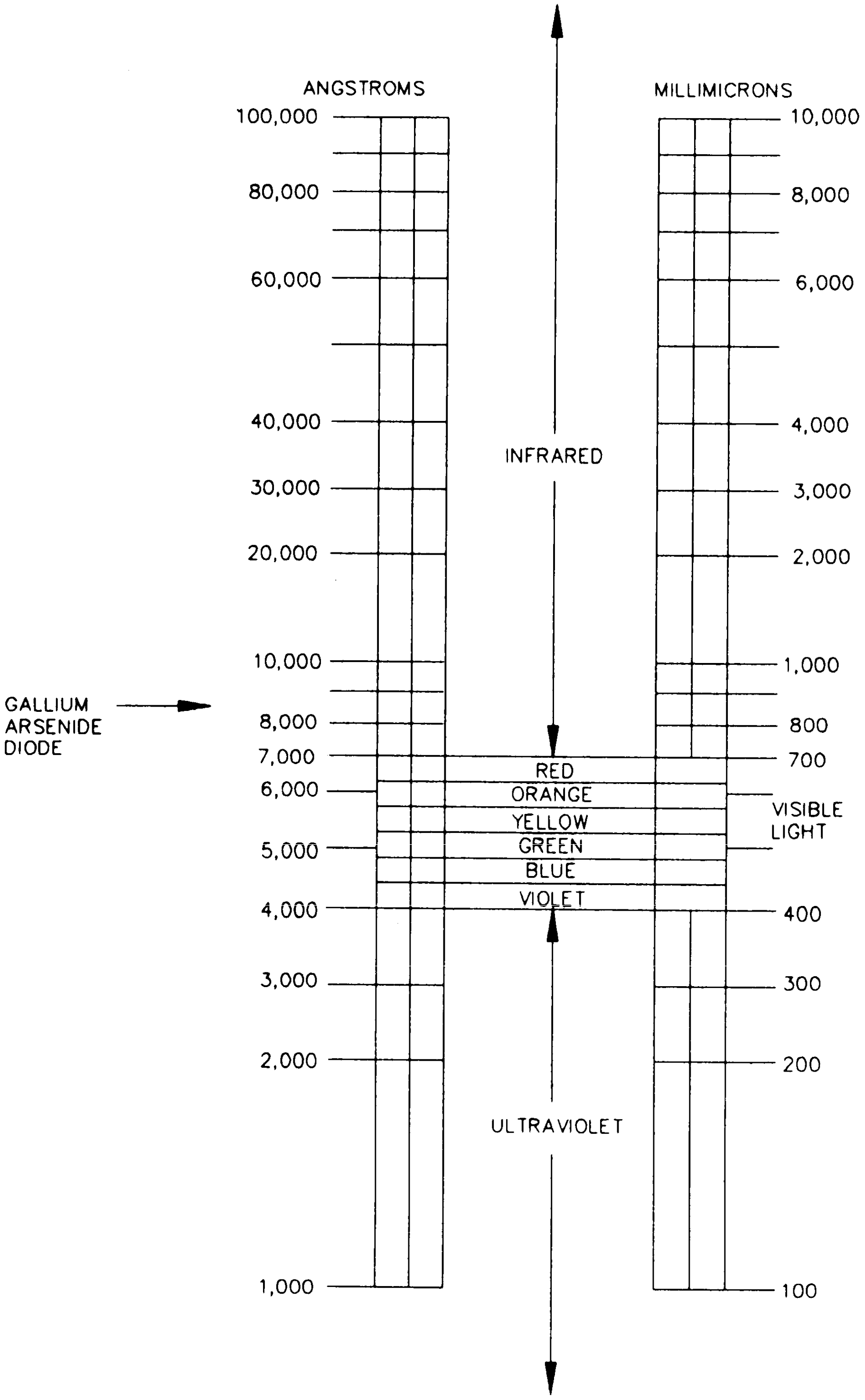


FIGURE 25. Light spectrum.

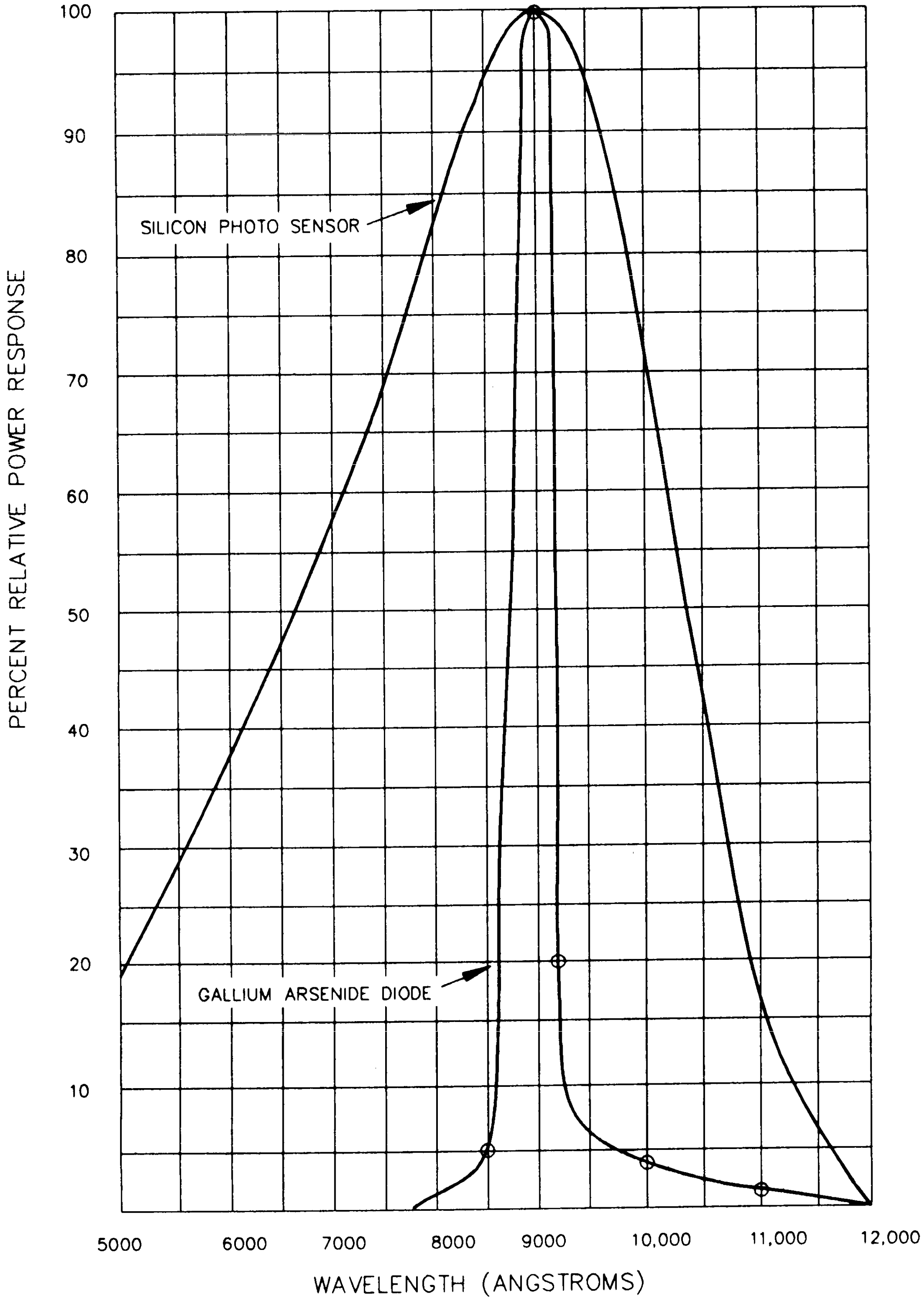


FIGURE 26. Spectral response, silicon photosensor and gallium arsenide diode, temperature constant.

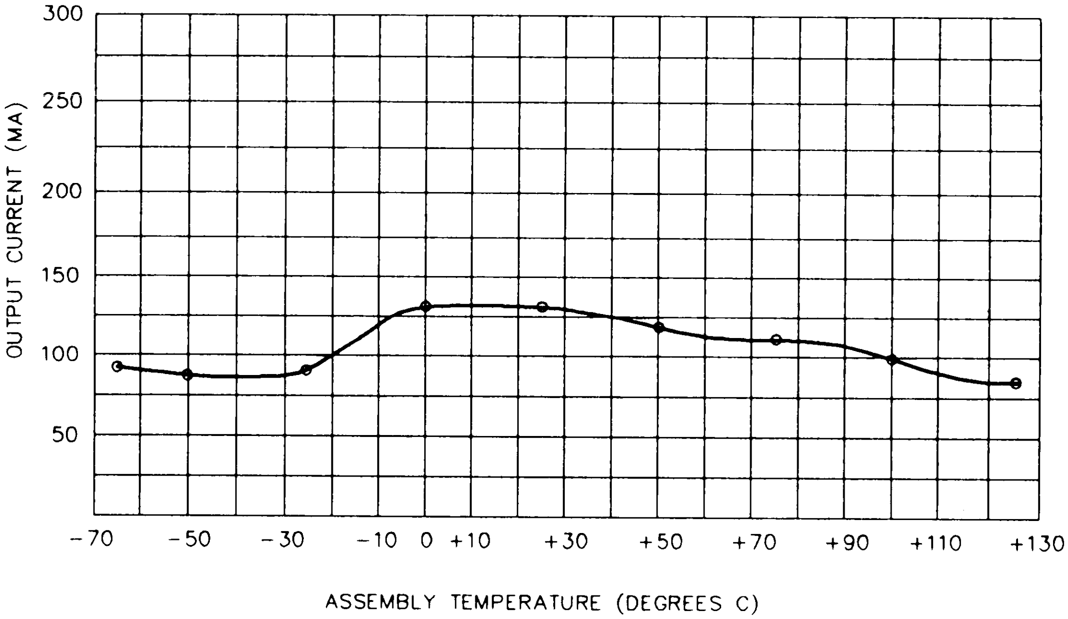


FIGURE 27. Gallium arsenide - silicon photocell detector assembly, output variations with temperature change (both components).

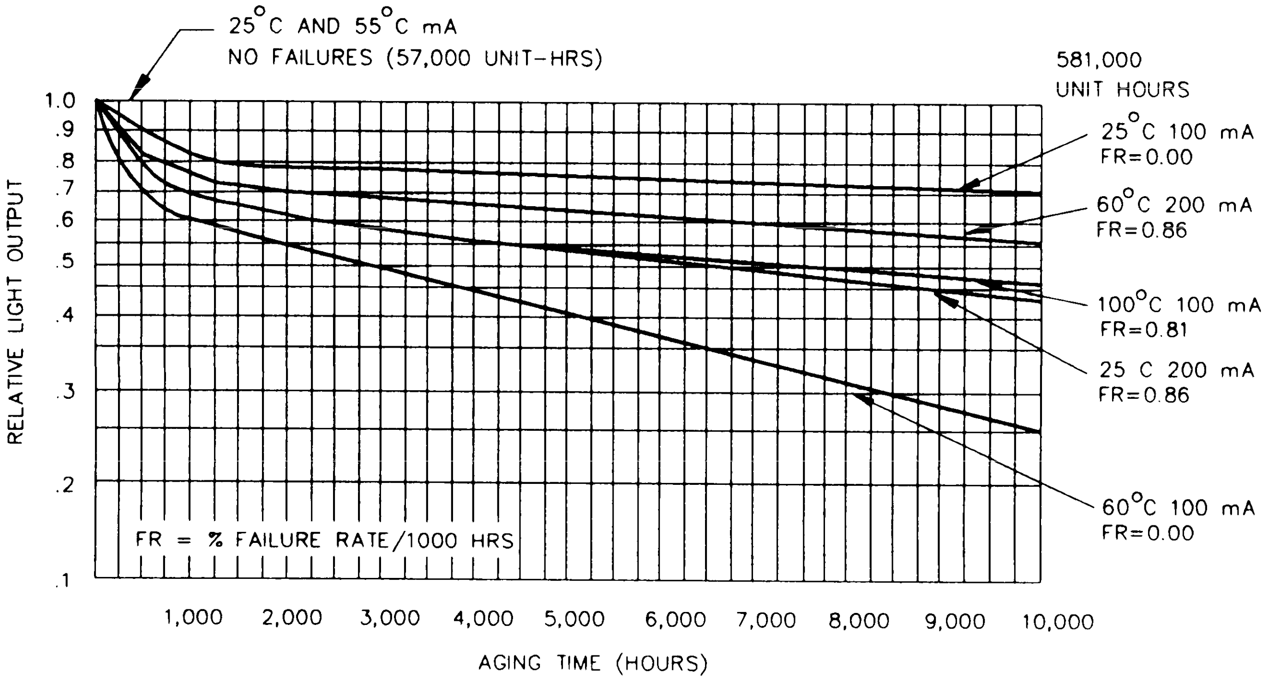


FIGURE 28. Gallium arsenide diode, reliability data.

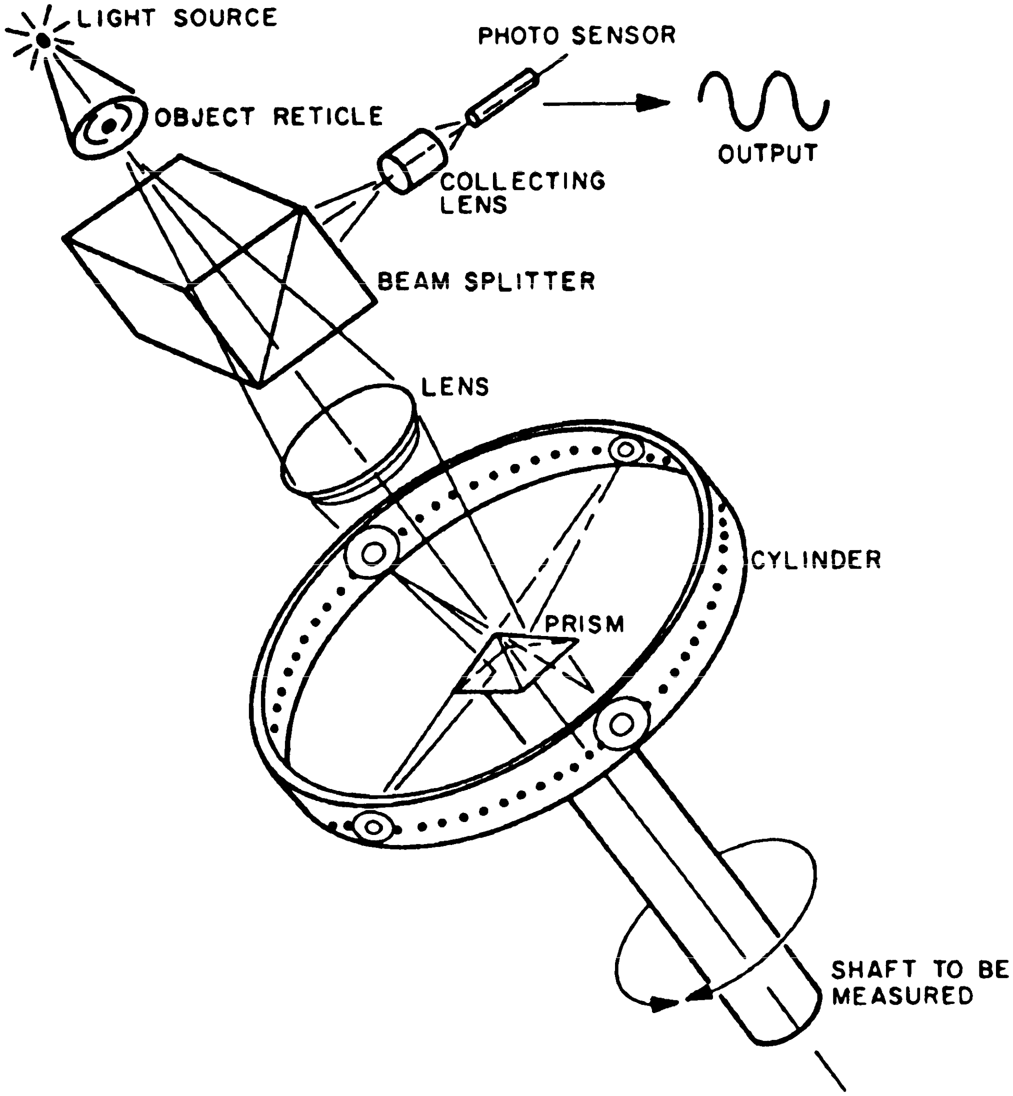
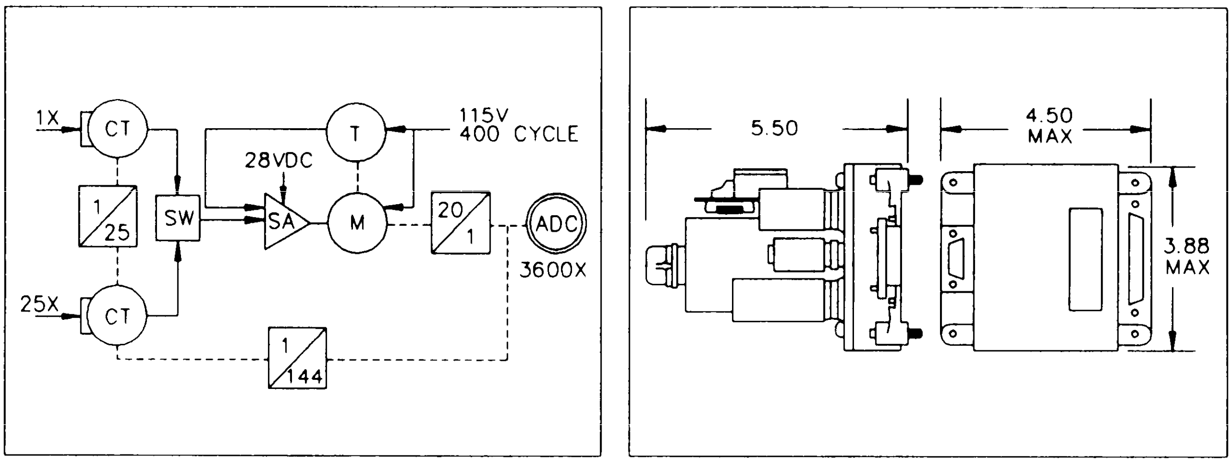


FIGURE 29. Energy coupled encoder.

LATITUDE



LONGITUDE

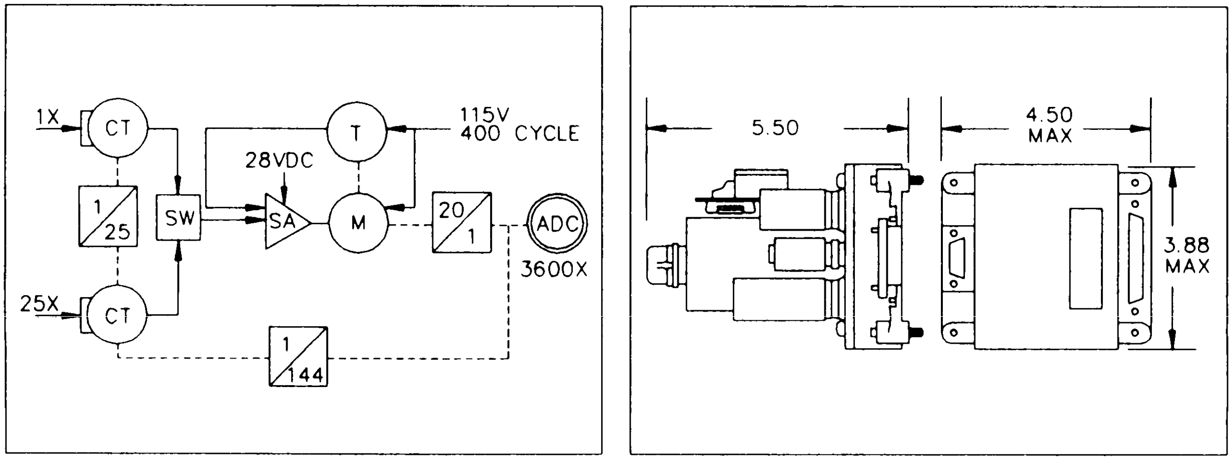
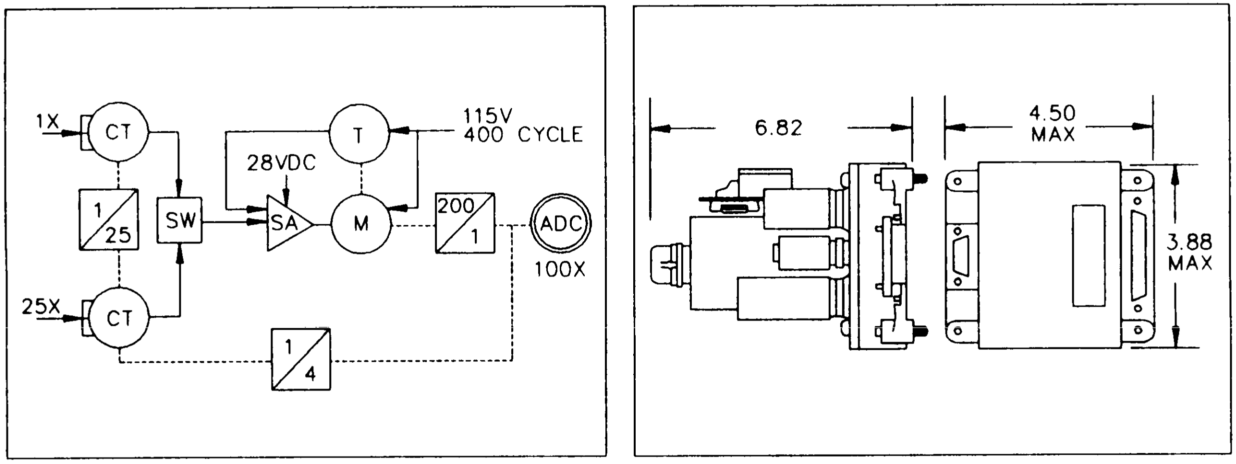
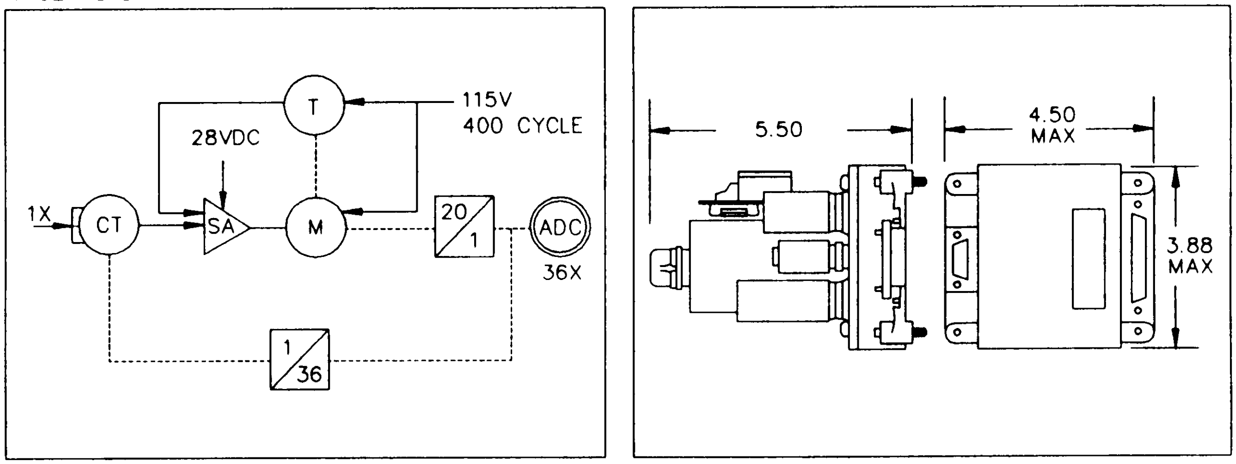


FIGURE 30. Navigational servo-encoder modules.

ALTITUDE



TRUE HEADING



GROUND SPEED

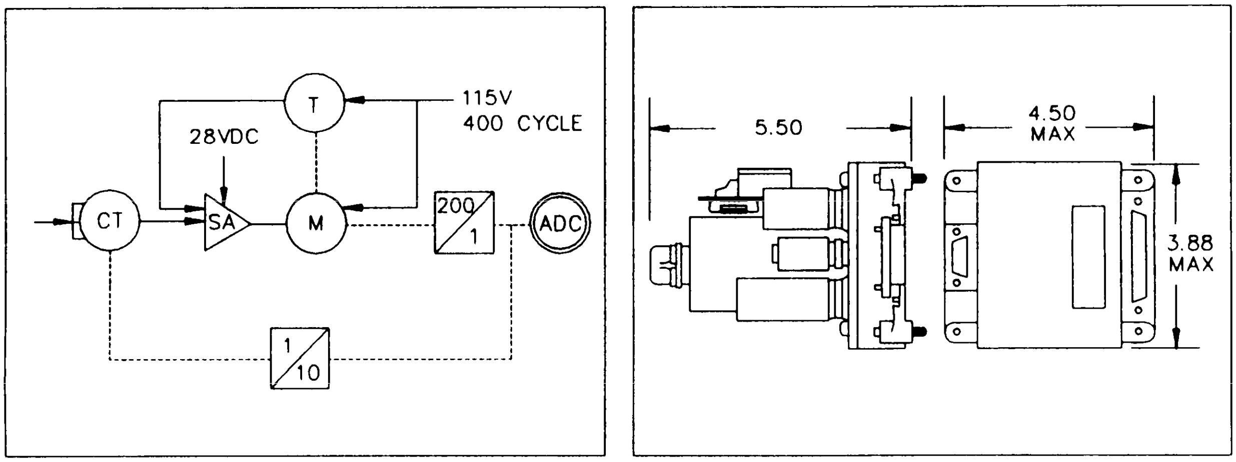


FIGURE 30. Navigational servo-encoder modules - Continued.

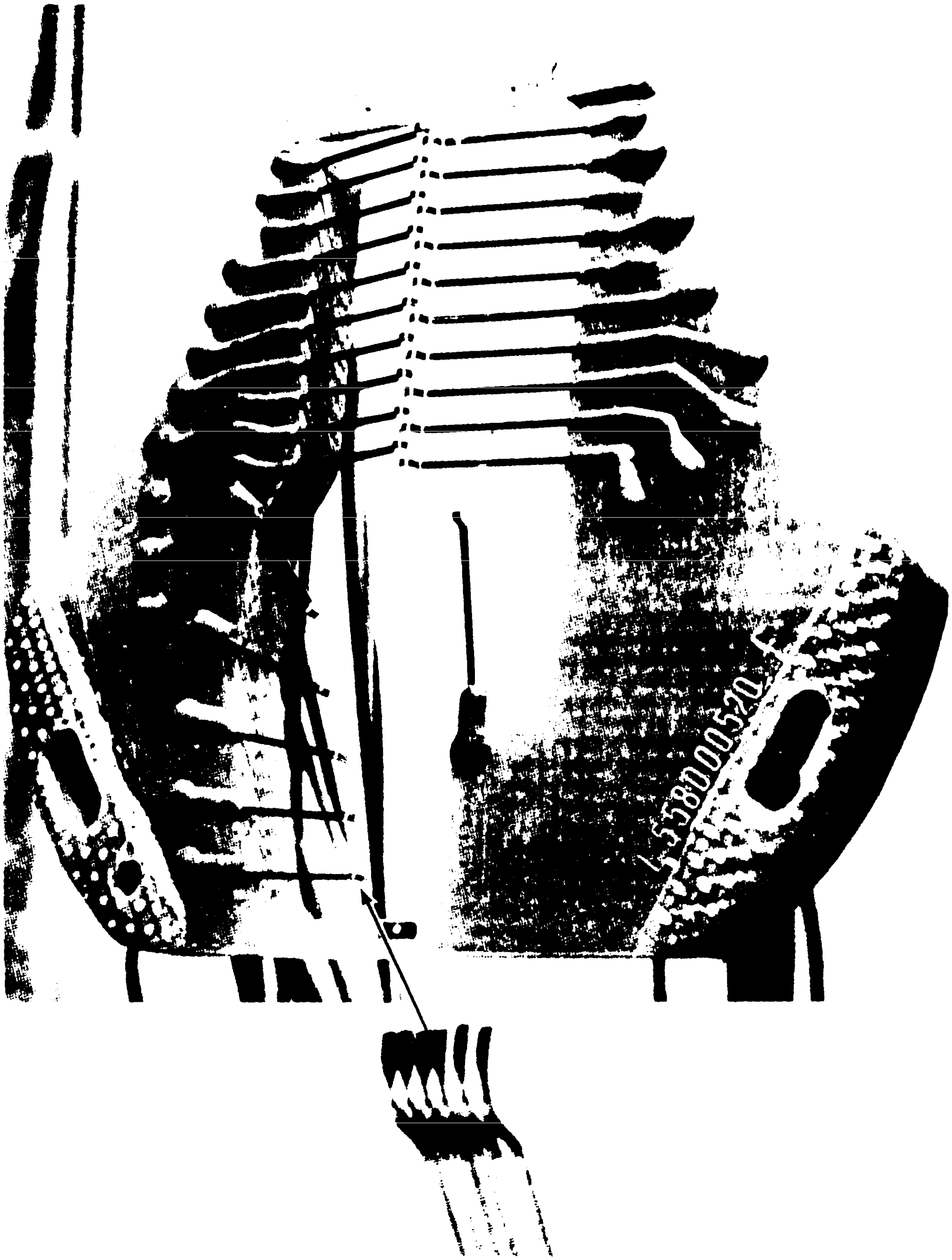


FIGURE 31. Brush and brush assembly.

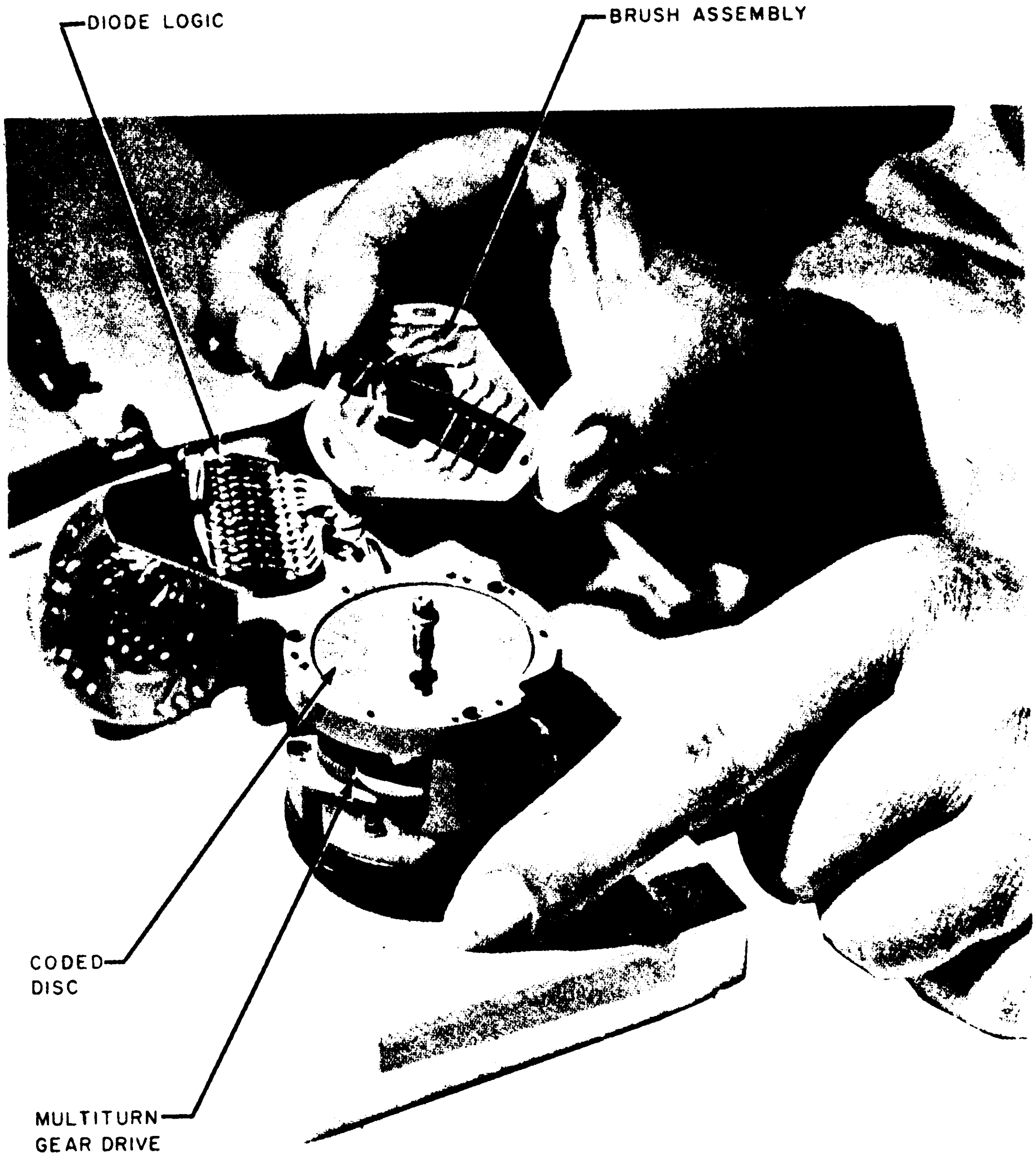
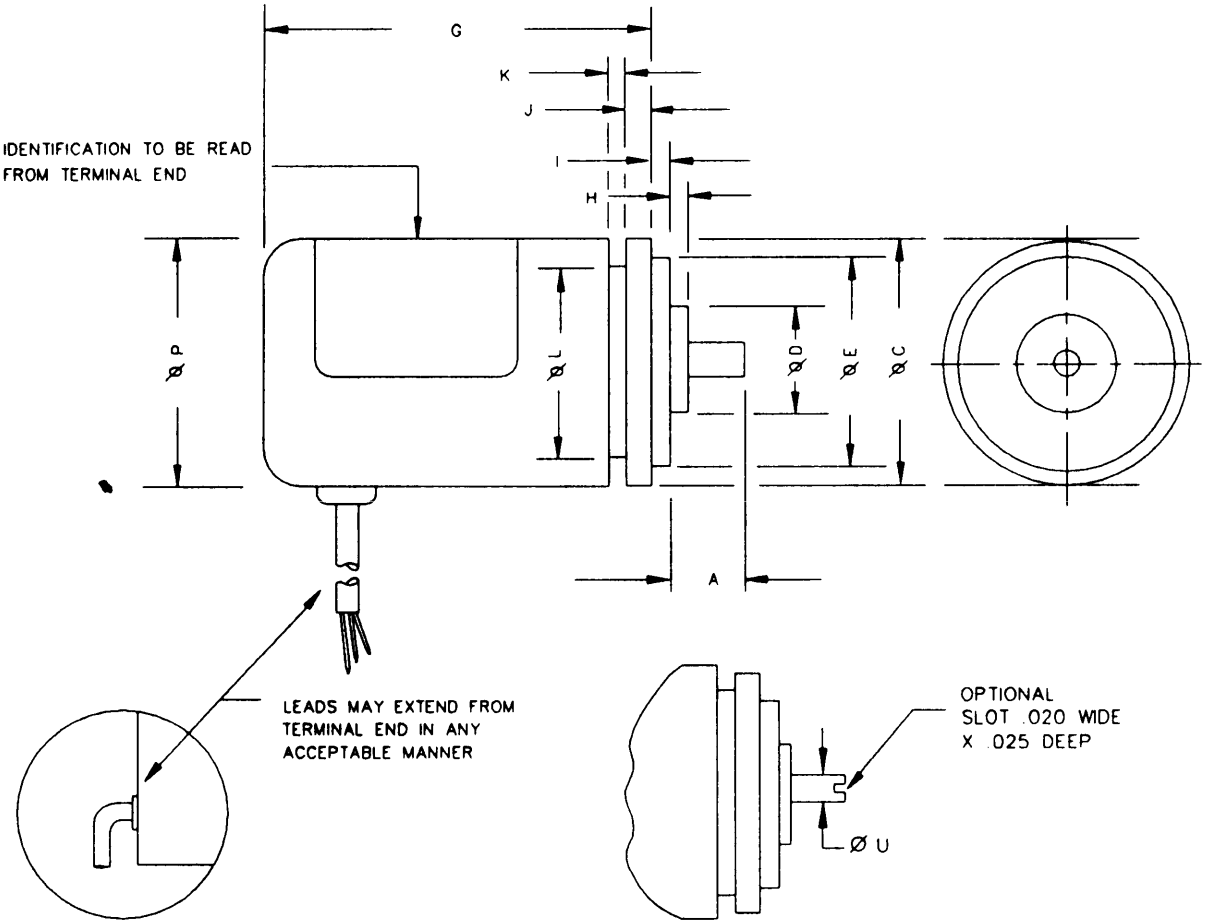


FIGURE 32. Brush encoder, cutaway view.



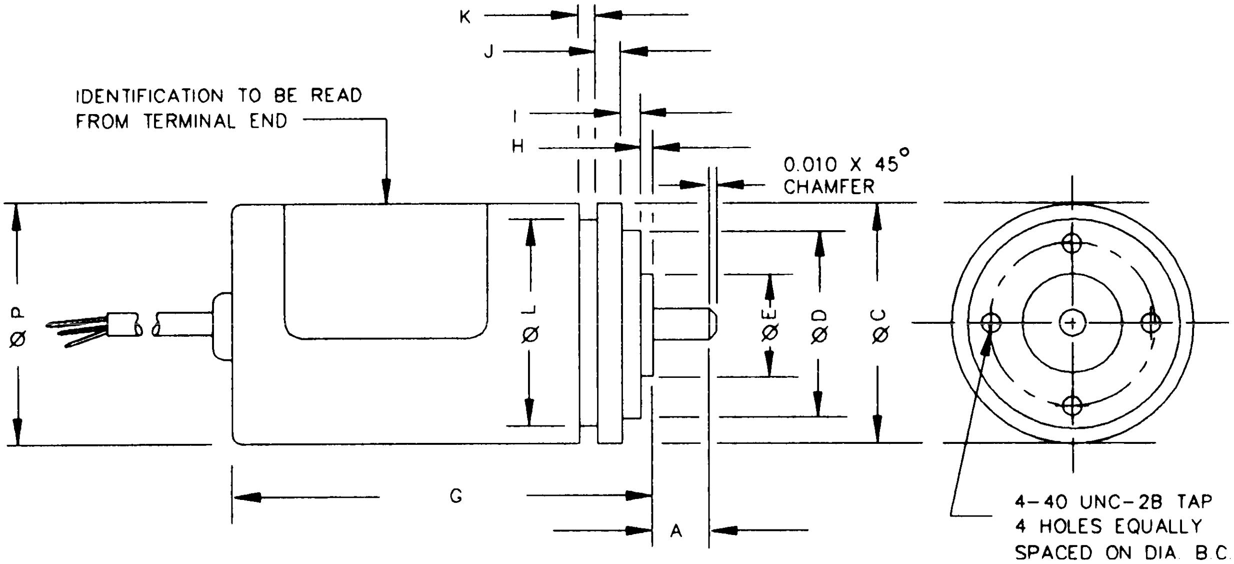
DIMENSIONS	A 1/	C	D	E 1/	G 1/	H 1/	I
ENCODER SIZE	±0.030	MAXIMUM	+0.0000 −0.0005	+0.0000 −0.0005	MAXIMUM	MAXIMUM	±0.003
SIZE 08	0.375	0.753	0.5000	----	2.600	0.040	----
SIZE 11	0.500	1.062	1.0000	0.6250	2.625	0.062	0.062

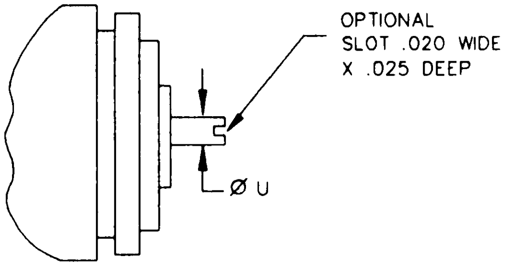
DIMENSIONS	J	K	L	P	U 1/	Z
ENCODER SIZE	±0.003	MAXIMUM	MAXIMUM	MAXIMUM	+0.0000 −0.0002	MAXIMUM
SIZE 08	0.062 ±0.005	0.049	0.670	----	0.1249	----
SIZE 11	0.093	0.050	0.975	1.062	0.1248	----

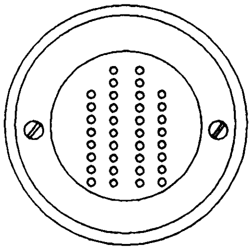
NOTE:

1/ THESE DIMENSIONS MAY VARY WITH DIFFERENT MANUFACTURERS.

FIGURE 33. Outline drawing for typical size 08 and 11 shaft angle encoders.







OPTIONAL TERMINAL END
FOR SIZE 18

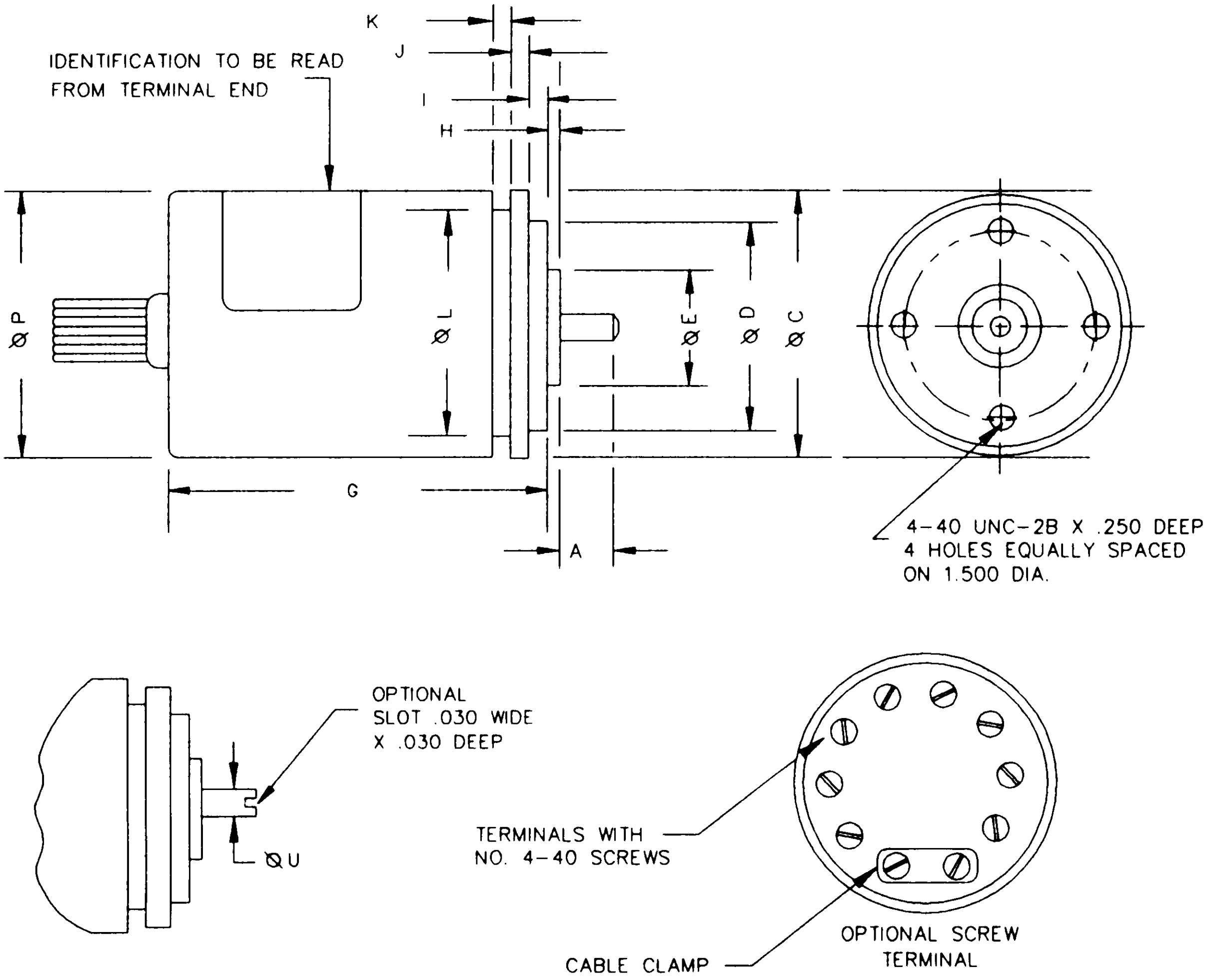
DIMENSIONS	A 1/	C	D	E 1/	G 1/	H 1/	I
ENCODER SIZE	MAXIMUM	MAXIMUM	+0.0000 -0.0005	+0.0000 -0.0005	MAXIMUM	±0.003	±0.003
SIZE 15	0.500	1.437	1.3120	0.8750	1.500	0.040	0.132
SIZE 18	0.390	1.750	1.5620	0.9375	3.615	0.040	0.132

DIMENSIONS	J	K	L	P	U 1/	Z
ENCODER SIZE	±0.003	±0.003	MAXIMUM	MAXIMUM	+0.0000 -0.0002	MAXIMUM
SIZE 15	0.093	0.078	1.312	1.500	0.1247	----
SIZE 18	0.093	0.078	1.625	1.750	0.1873	----

NOTE:

1/ THESE DIMENSIONS MAY VARY WITH DIFFERENT MANUFACTURERS.

FIGURE 34. Outline drawing for typical size 15 and 18 shaft angle encoders.

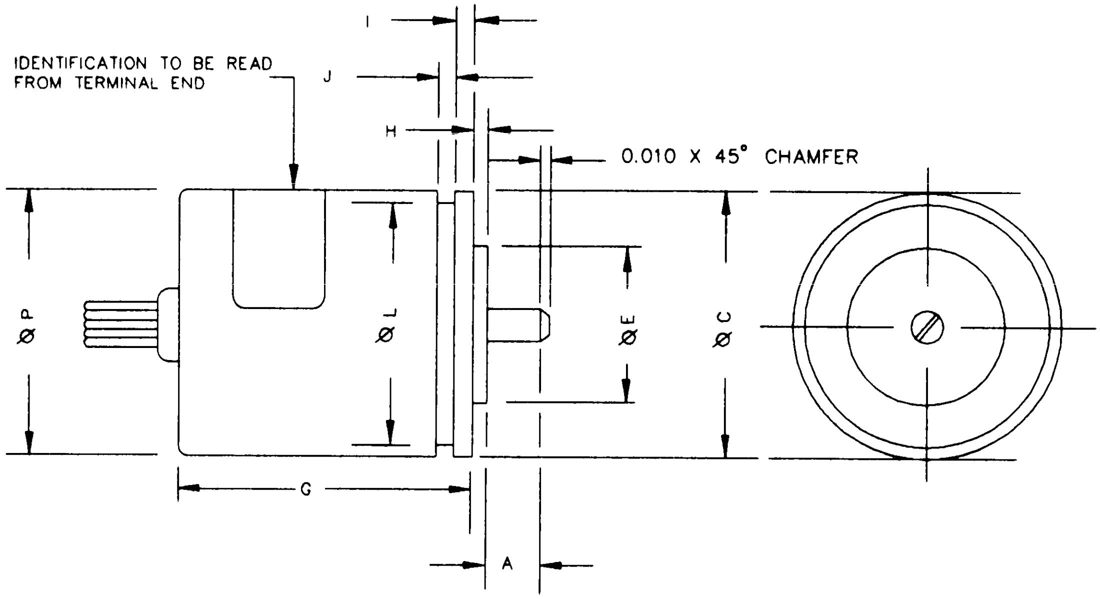


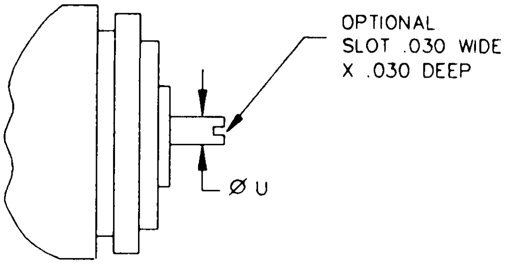
DIMENSIONS	A 1/	C	D	E 1/	G 1/	H 1/	I
ENCODER SIZE	±0.015	MAXIMUM	+0.0000 -0.0005	+0.0000 -0.0005	MAXIMUM	±0.003	±0.003
SIZE 23	0.0610	2.250	2.0000	0.9375	3.75	0.062	0.200

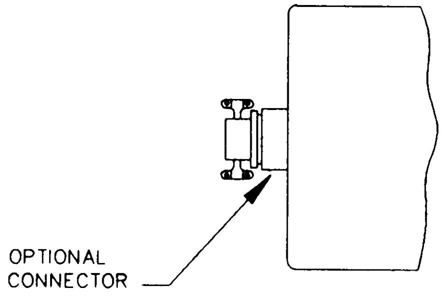
DIMENSIONS	J	K	L	P	U 1/	Z
ENCODER SIZE	±0.003	±0.003	±0.003	MAXIMUM	+0.0000 -0.0002	MAXIMUM
SIZE 23	0.125	0.095	2.062	2.300	0.2498	----

NOTE:
1/ THESE DIMENSIONS MAY VARY WITH DIFFERENT MANUFACTURERS.

FIGURE 35. Outline drawing for typical size 23 shaft angle encoder.







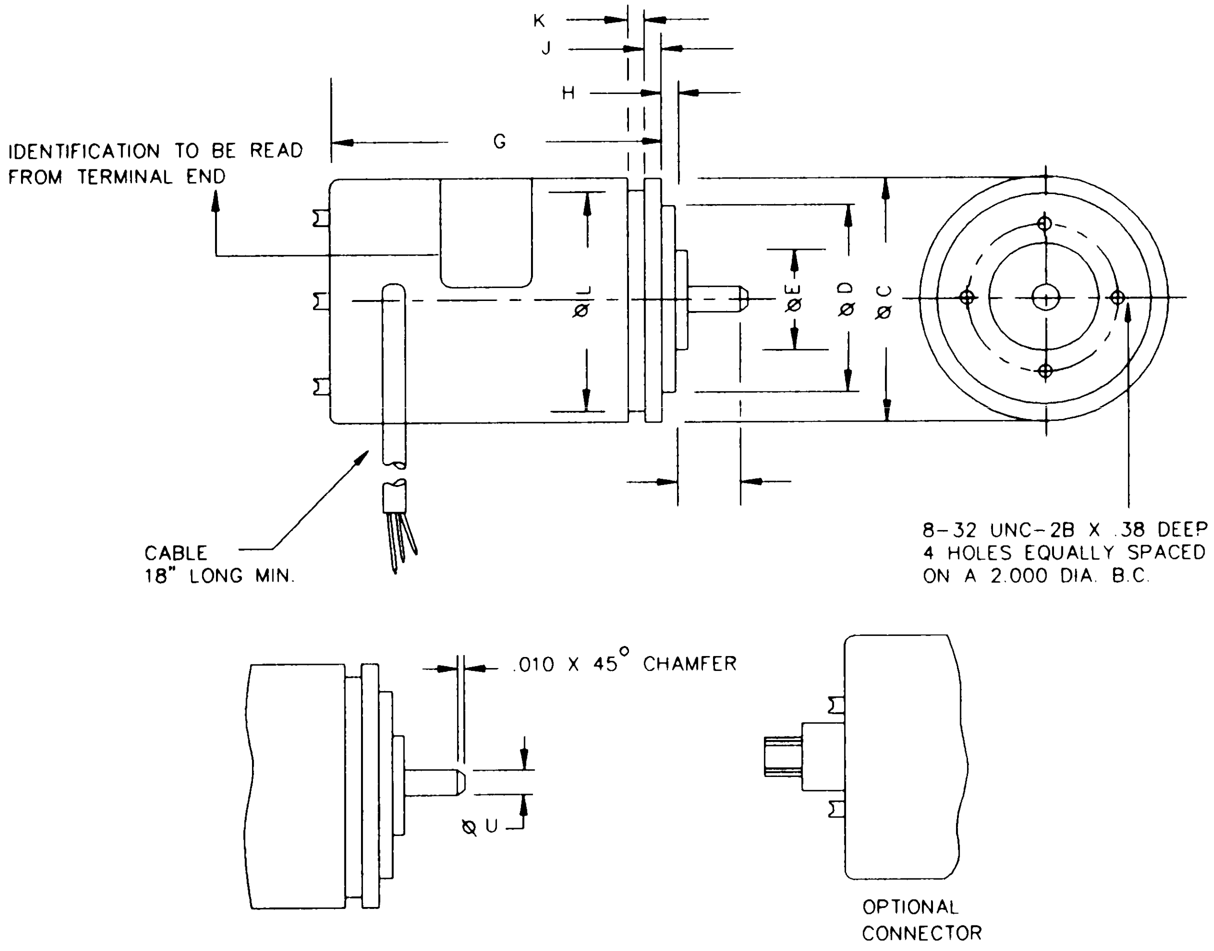
DIMENSIONS	A 1/	C	D	E 1/	G 1/	H	I
ENCODER SIZE	±0.015	MAXIMUM	+0.0000 −0.0005	+0.0000 −0.0005	MAXIMUM	±0.003	±0.003
SIZE 31	0.562	3.062	----	1.3120	5.000	0.132	----

DIMENSIONS	J	K	L	P	U 1/	Y	Z
ENCODER SIZE	±0.003	±0.003	MAXIMUM	MAXIMUM	+0.0000 −0.0002	MAXIMUM	MAXIMUM
SIZE 31	0.093	0.078	2.937	----	0.2498	----	----

NOTE:

1/ THESE DIMENSIONS MAY VARY WITH DIFFERENT MANUFACTURERS.

FIGURE 36. Outline drawing for typical size 31 shaft angle encoder.



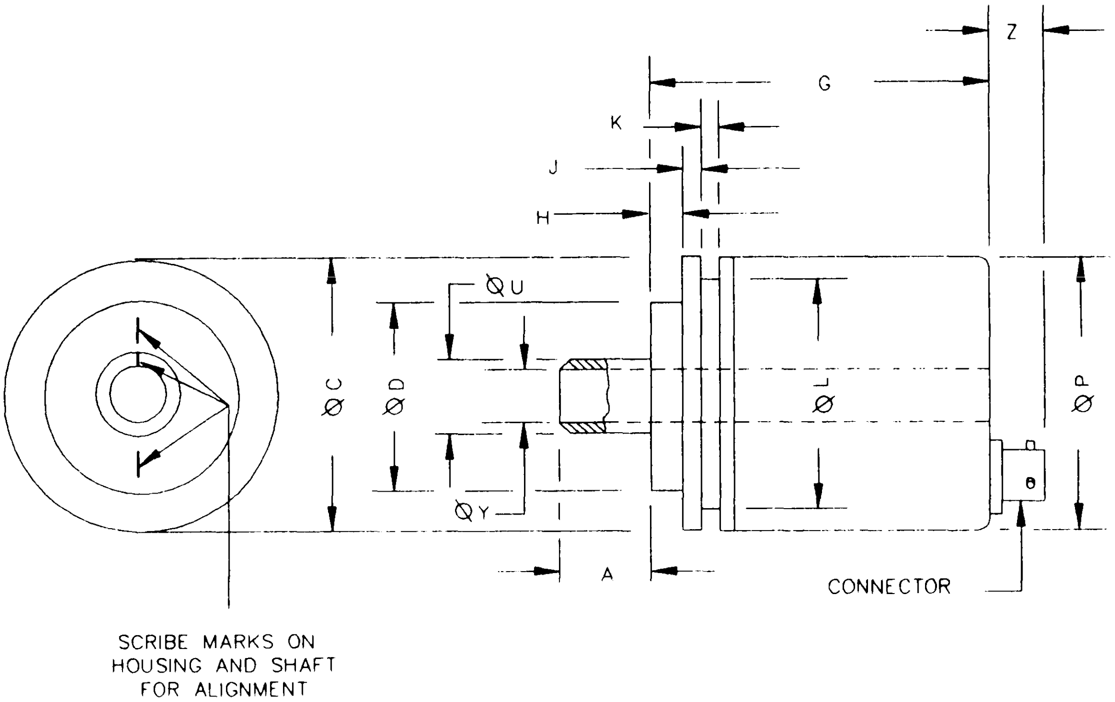
DIMENSIONS	A 1/	C	D 1/	E 1/	G 1/	H 1/	I 1/
ENCODER SIZE	±0.020	+0.003 -0.010	+0.000 -0.001	+0.000 -0.001	MAXIMUM	±0.004	±0.004
SIZE 35	1.000	3.500	3.125	1.500	3.00	0.160	0.125

DIMENSIONS	J 1/	K	L 1/	P	U 1/	Y	Z
ENCODER SIZE	±0.004	±0.004	±0.006	MAXIMUM	+0.0000 -0.0002	MAXIMUM	MAXIMUM
SIZE 35	0.100	0.100	3.290	----	0.2498	----	----

NOTE:

1/ THESE DIMENSIONS MAY VARY WITH DIFFERENT MANUFACTURERS.

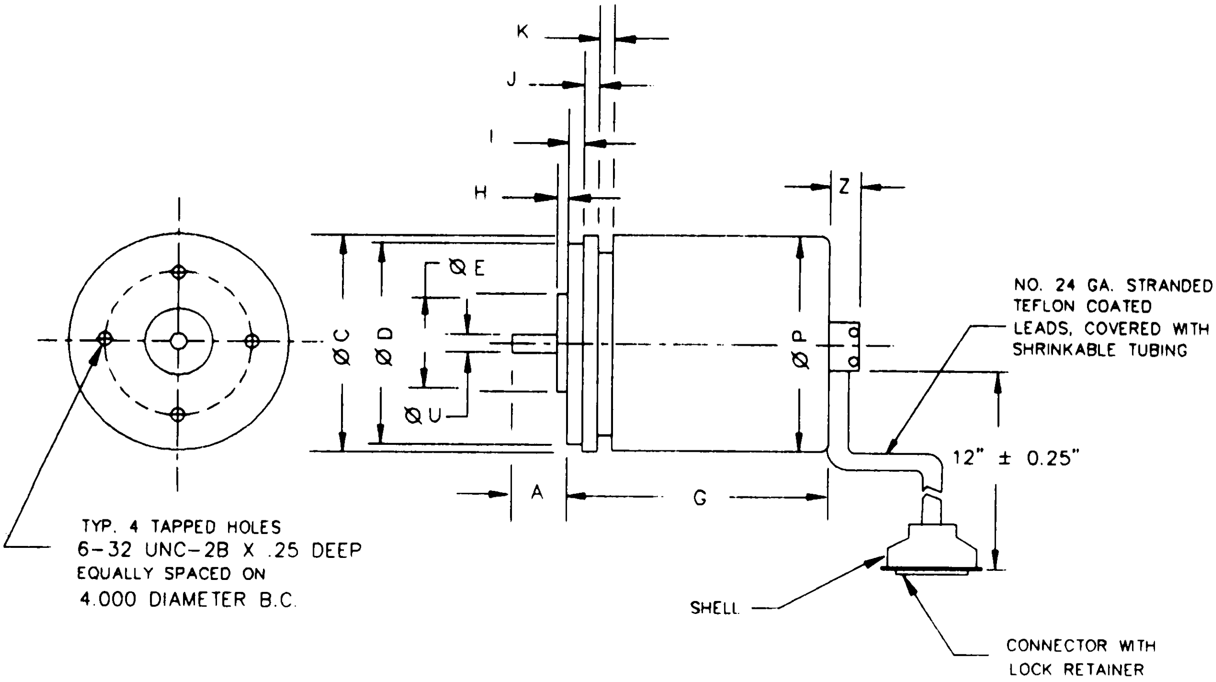
FIGURE 37 Outline drawing for typical size 35 shaft angle encoder.



DIMENSIONS	A	C	D	E	G	H	I
ENCODER SIZE	±0.03	±0.005	+0.000 −0.001	+0.000 −0.001	MAXIMUM	±0.010	±0.005
SIZE 40 HOLLOW SHAFT	1.00	4.000	2.562	----	3.18	0.310	----

DIMENSIONS	J	K	L	P	U	Y	Z
ENCODER SIZE	±0.005	±0.005	MAXIMUM	±0.016	+0.000 −0.001	+0.015 −0.000	MAXIMUM
SIZE 40 HOLLOW SHAFT	0.125	0.150	3.760	4.000	0.875	0.690	0.562

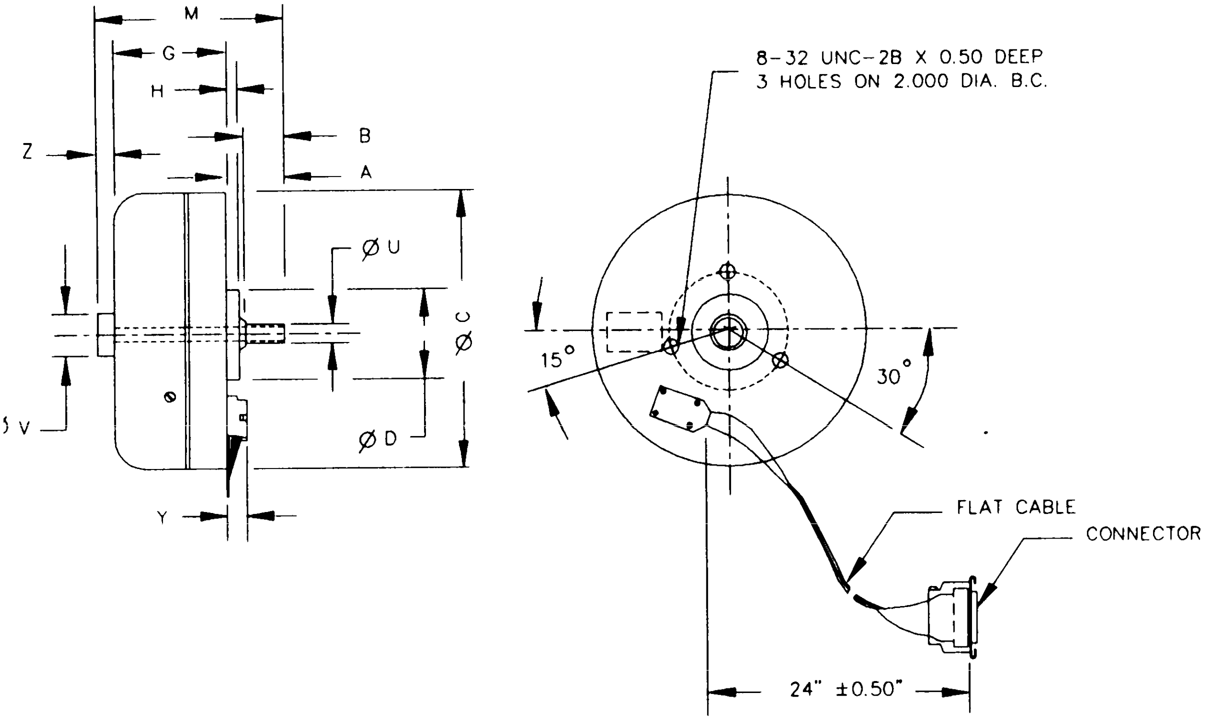
FIGURE 38. Outline drawing for typical size 40 hollow shaft encoder.



DIMENSIONS	A	C	D	E	G	H	I
ENCODER SIZE	MAXIMUM	±0.005	+0.0000 −0.0005	+0.0000 −0.0005	MAXIMUM	±0.003	±0.003
SIZE 55	0.500	5.500	5.3750	1.5000	3.125	0.040	0.062

DIMENSIONS	J	K	L	P	U	Y	Z
ENCODER SIZE	±0.003	±0.003	MAXIMUM	±0.005	+0.0000 −0.0002	MAXIMUM	MAXIMUM
SIZE 55	0.062	0.062	----	5.500	0.2498	----	0.40

FIGURE 39. Outline drawing for typical size 55 shaft angle encoder.



DIMENSIONS	A	B	C	D	E	G	H
ENCODER SIZE	±0.040	MAXIMUM	MAXIMUM	±0.0002	+0.000 -0.001	MAXIMUM	MAXIMUM
SIZE 65	0.613	0.440	6.50	1.1248	----	2.062	0.049

DIMENSIONS	L	M	P	U	V	Y	Z
ENCODER SIZE	MAXIMUM	MAXIMUM	MAXIMUM	+0.000 -0.002	+0.0000 -0.0005	MAXIMUM	MAXIMUM
SIZE 65	----	2.75	----	0.438	0.3755	0.370	0.032

FIGURE 40. Outline drawing for typical size 65 shaft angle encoder.

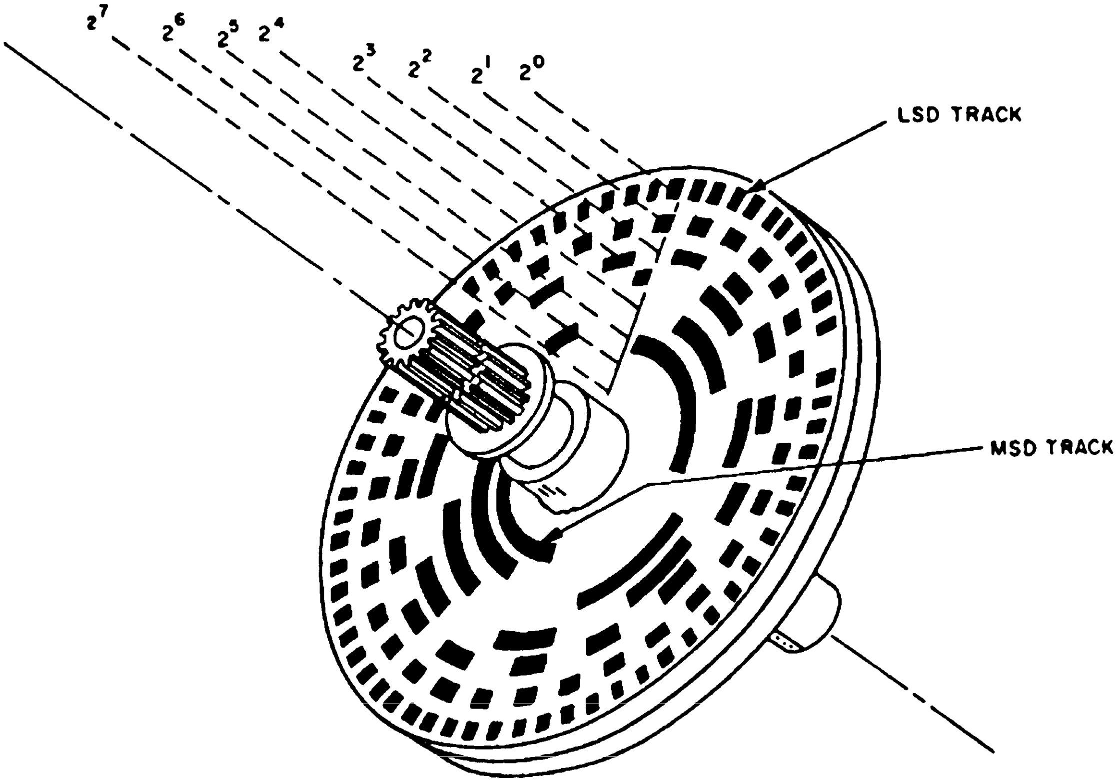


FIGURE 41. Concentric track disc (2^8).

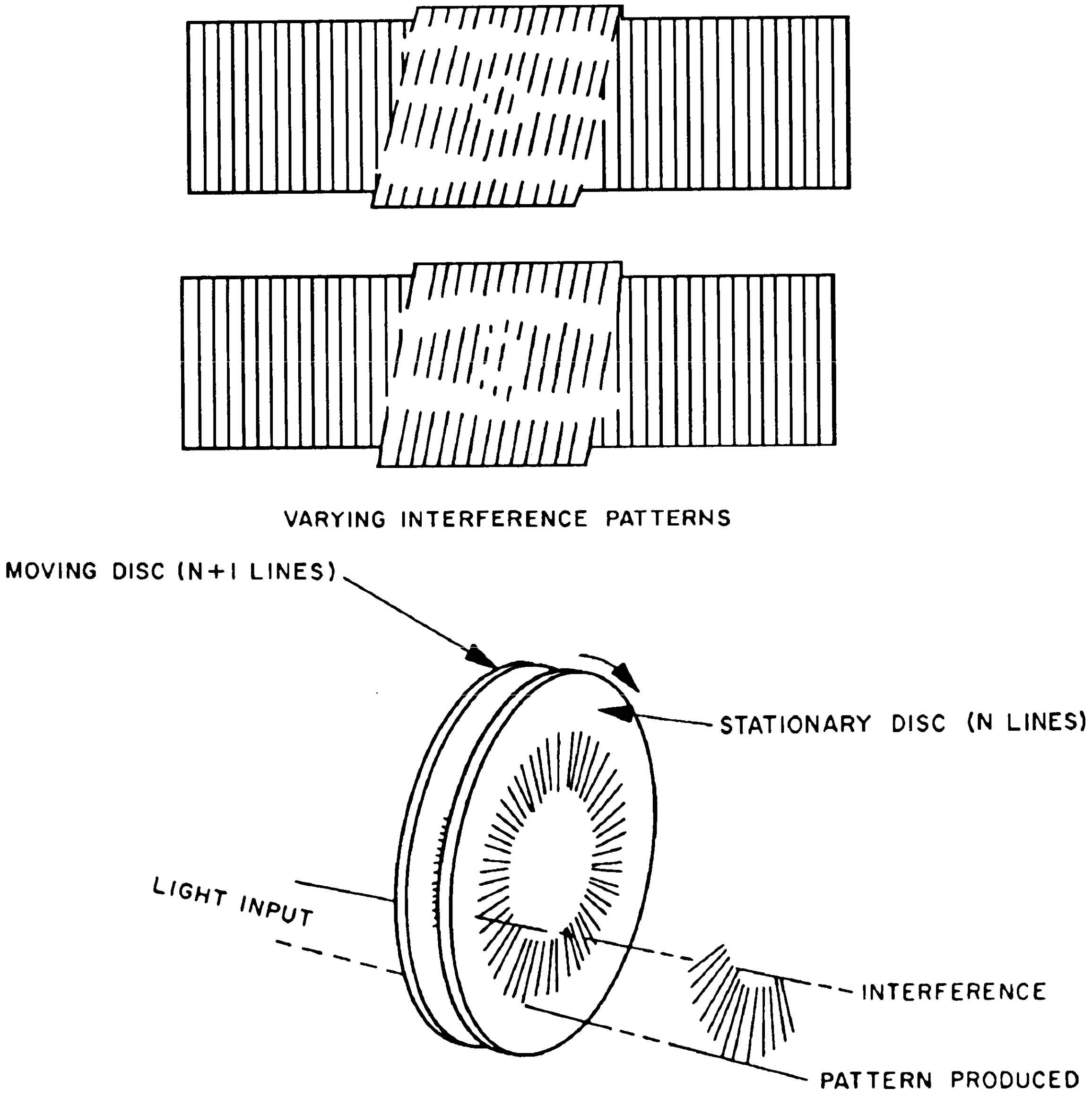


FIGURE 42. Moire fringe patterns.

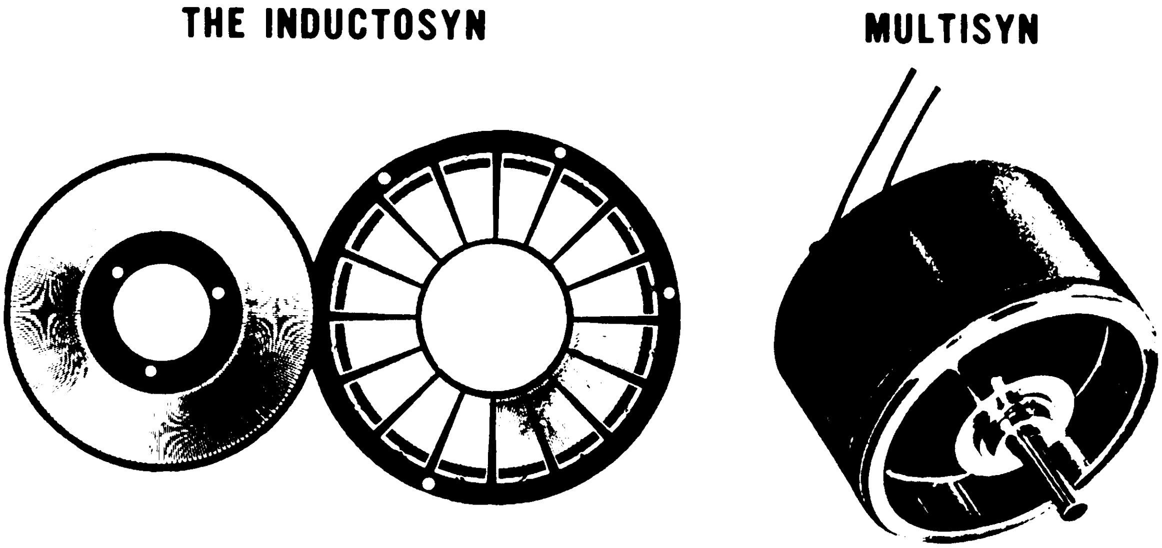


FIGURE 43. Inductive encoder, cutaway view.

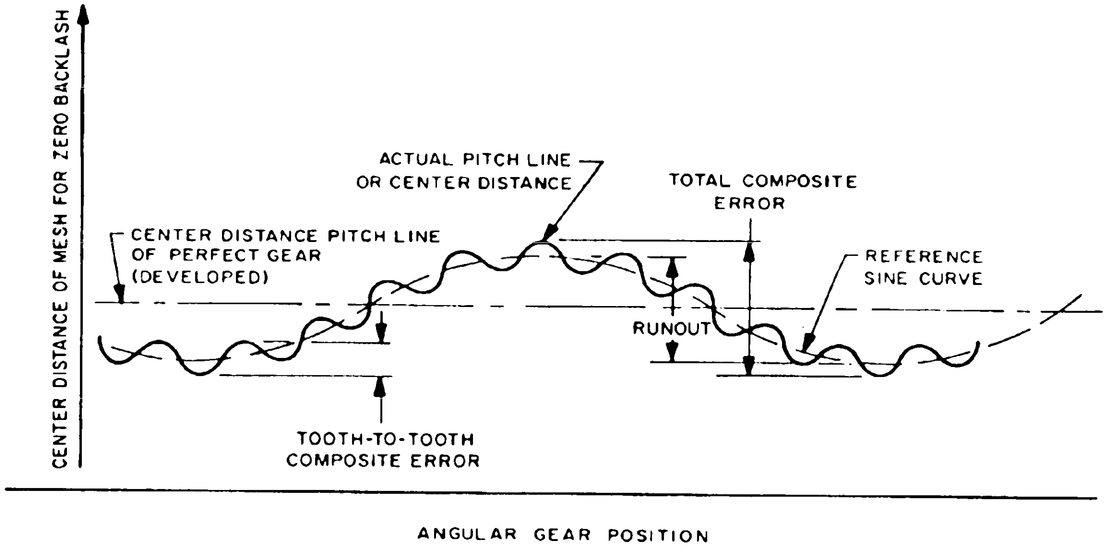


FIGURE 44. Gear test tape of gear errors.

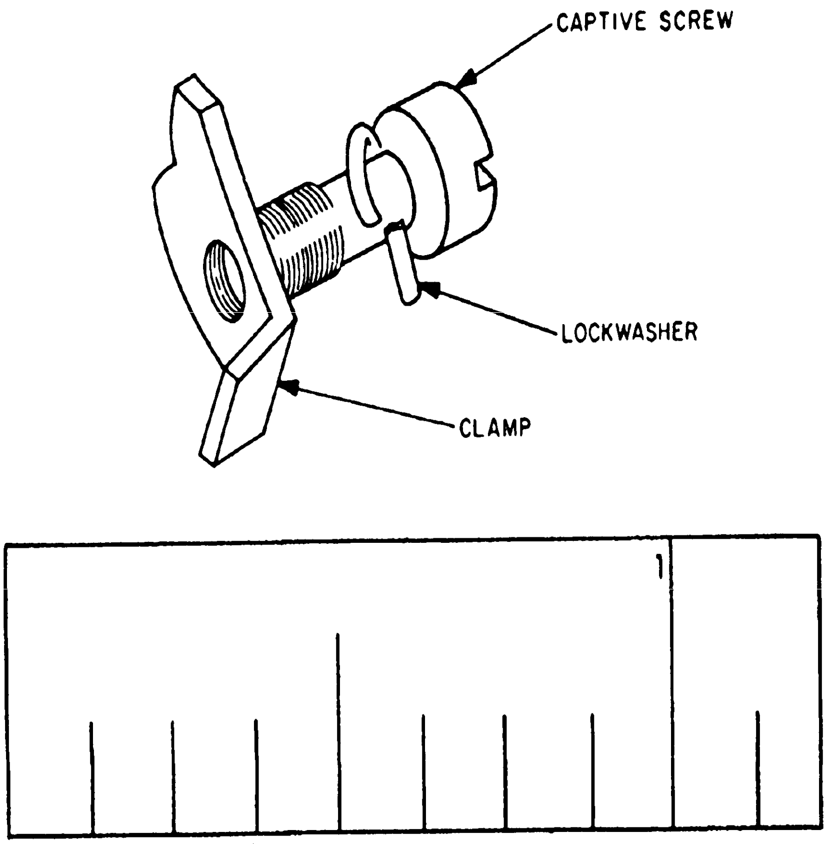


FIGURE 45. Mounting clamp assembly.

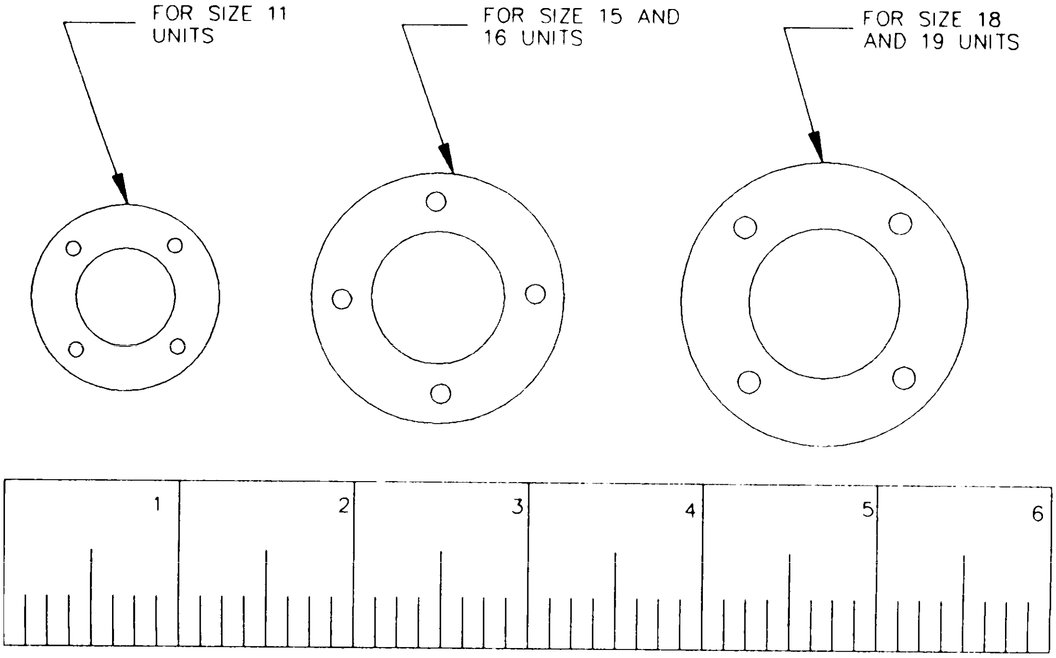


FIGURE 46. Clamping disc.

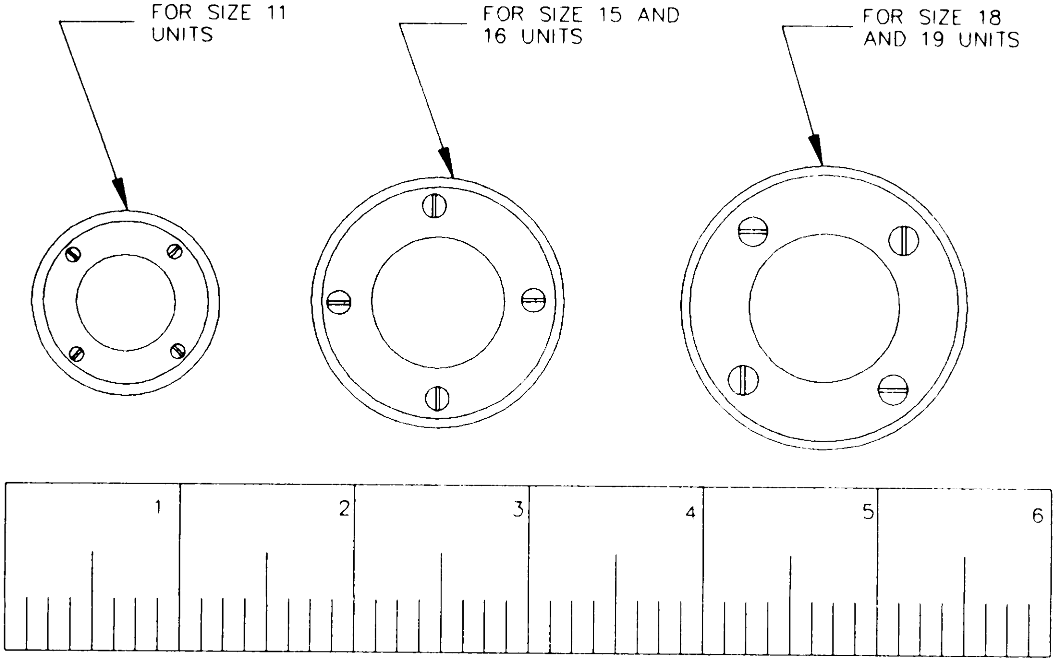


FIGURE 47. Adapter assemblies.

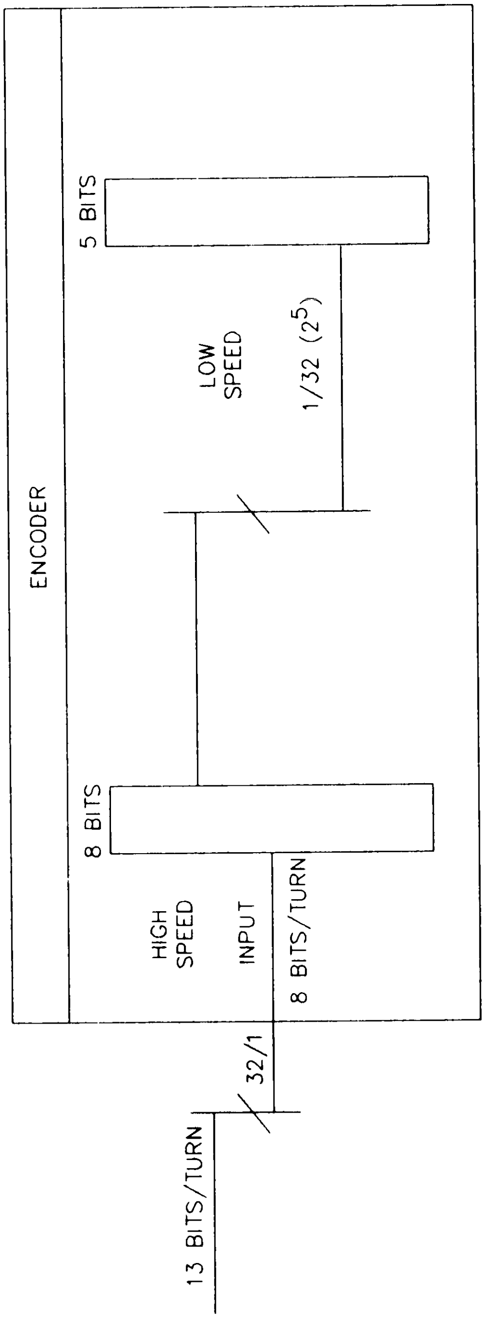


FIGURE 48. Input processing for typical multi-turn encoder.

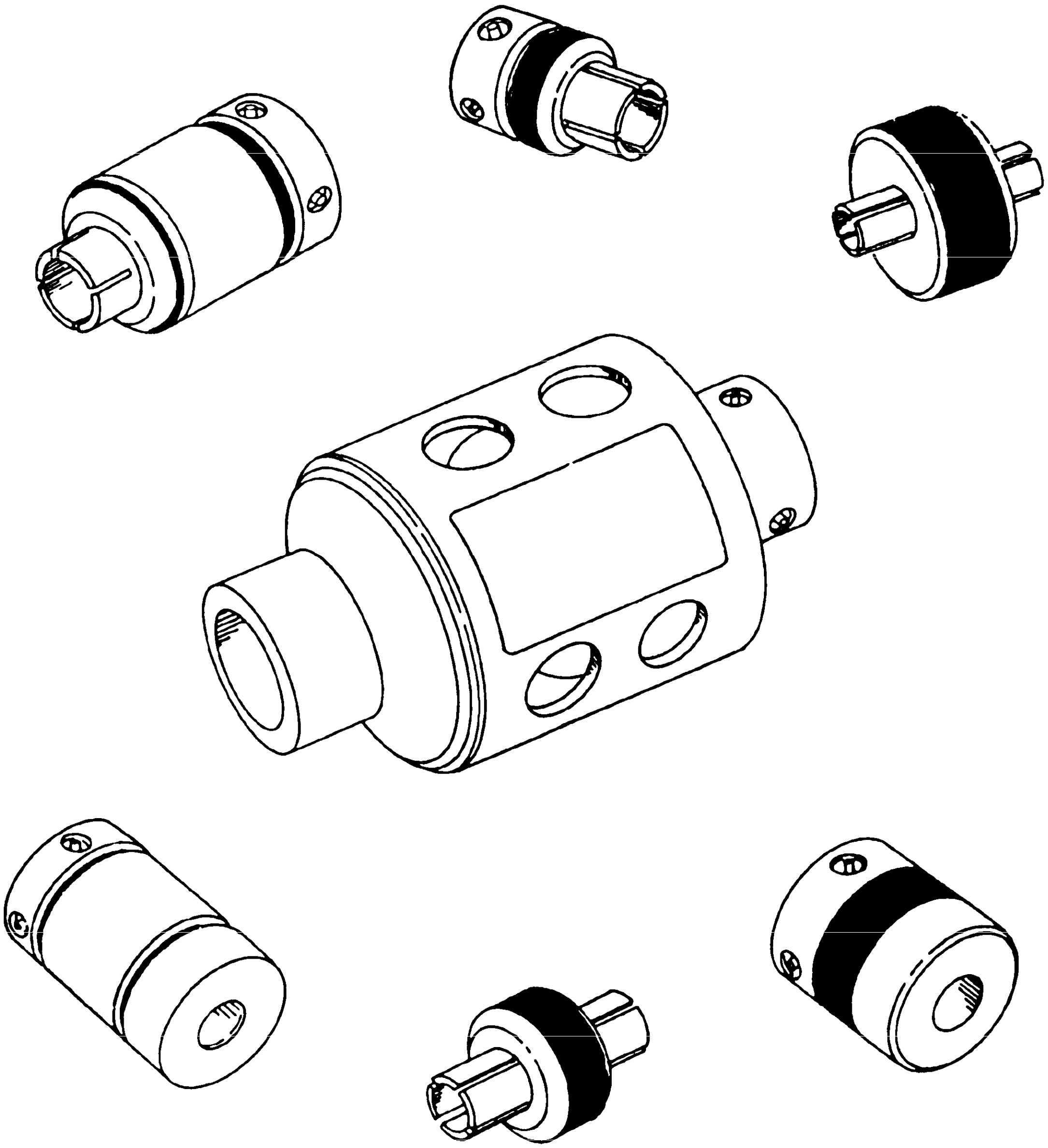


FIGURE 49. Typical encoder couplings.

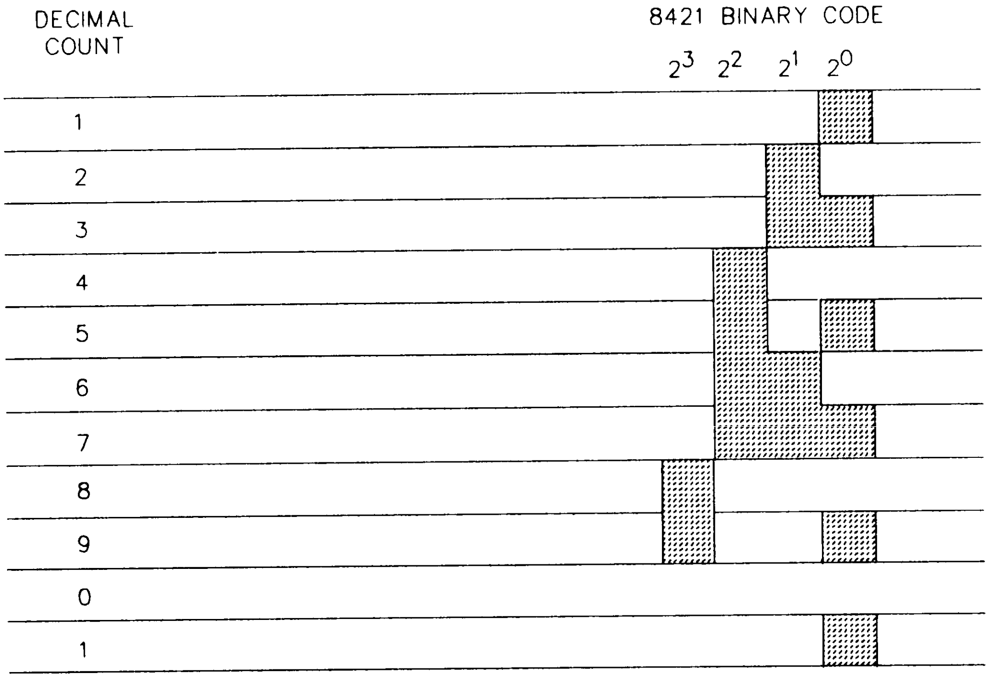
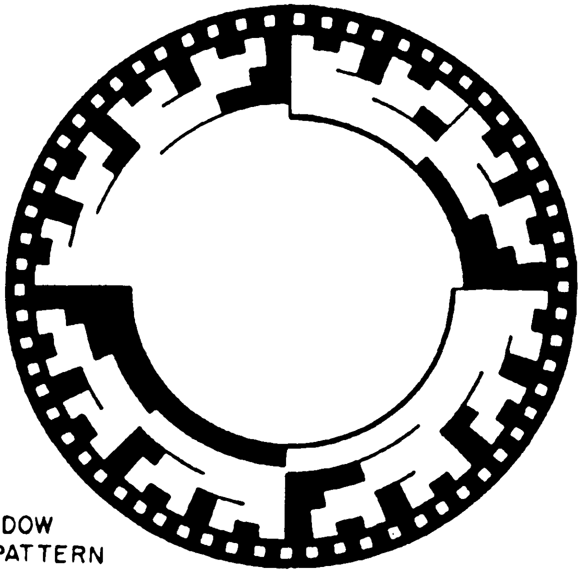


FIGURE 50. Ambiguous 8421 natural binary code.



TYPICAL WINDOW CODE DISC PATTERN

DECIMAL COUNT	8421 BINARY CODE 8	4	2	1	WINDOW
0					▨
1				▨	▨
2			▨		▨
3			▨	▨	▨
4		▨			▨
5		▨		▨	▨
6		▨	▨		▨
7		▨	▨	▨	▨
8	▨				▨
9	▨			▨	▨

FIGURE 51. Typical window code.

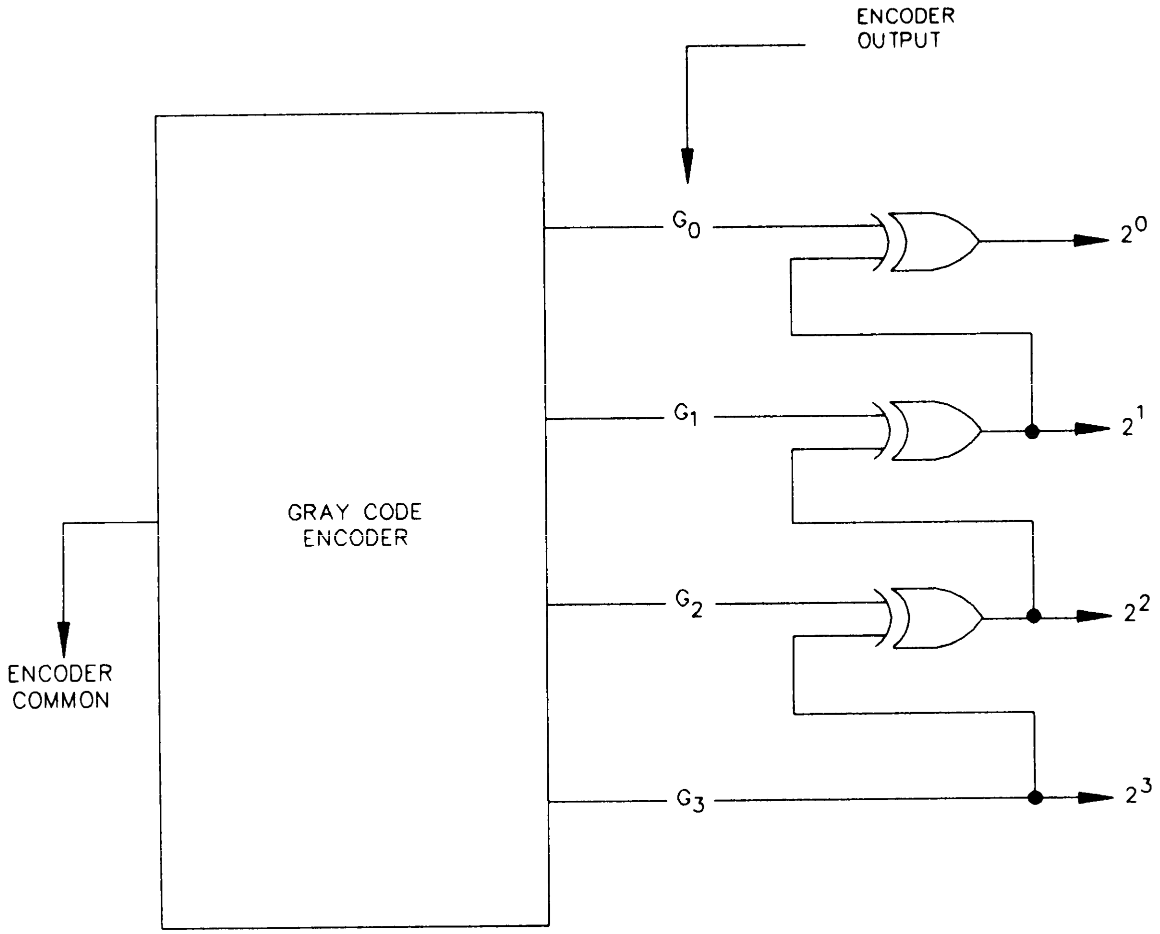
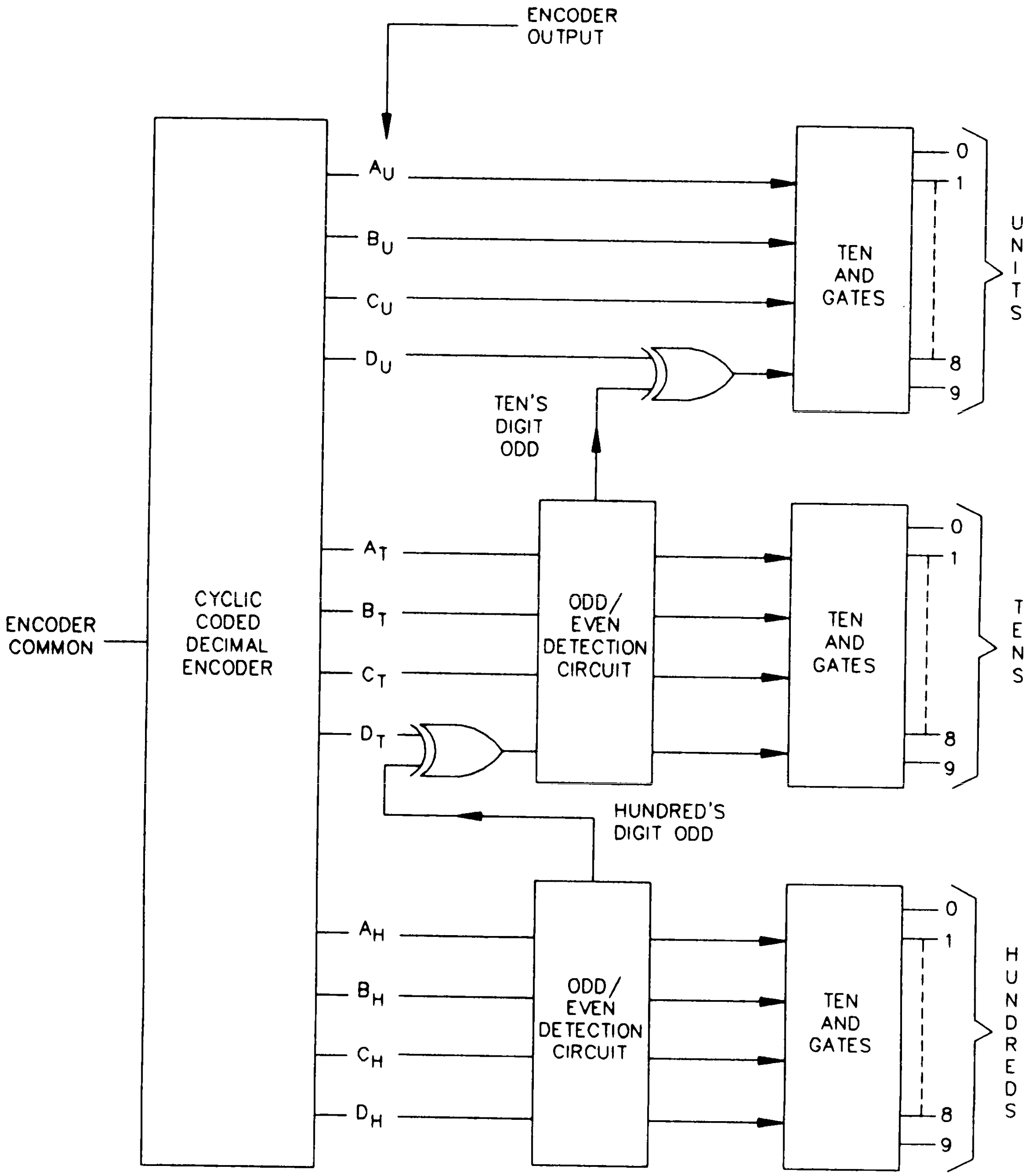


FIGURE 52. Typical non-ambiguous gray code scheme.



NOTE:

1. EXCLUSIVE OR CIRCUIT (OUTPUT TRUE, LOGICAL "1"; IF EITHER, BUT NOT BOTH, INPUTS ARE TRUE, LOGICAL "1").

FIGURE 53. Typical cyclic-coded decimal encoder scheme.

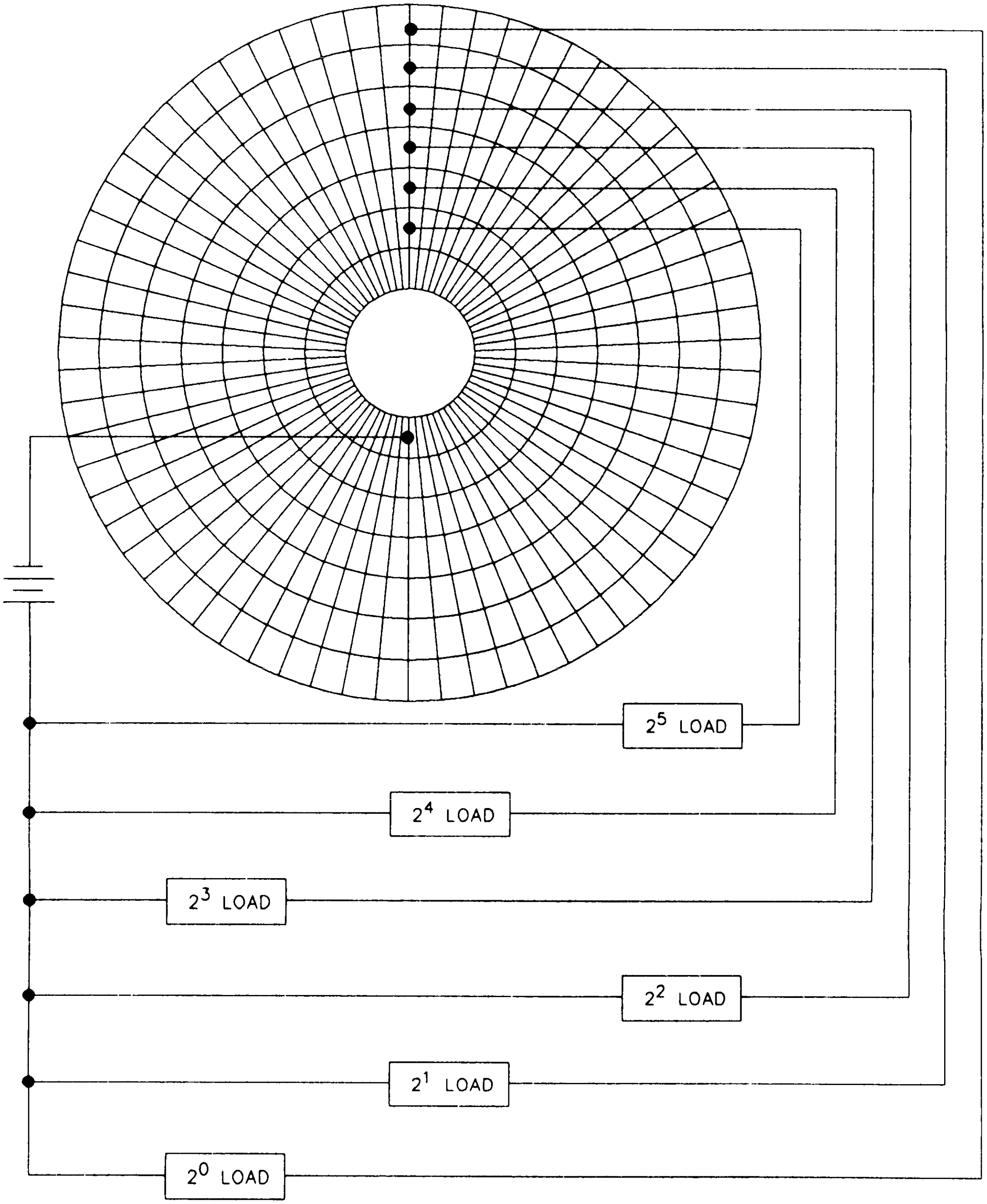


FIGURE 54. Line scan.

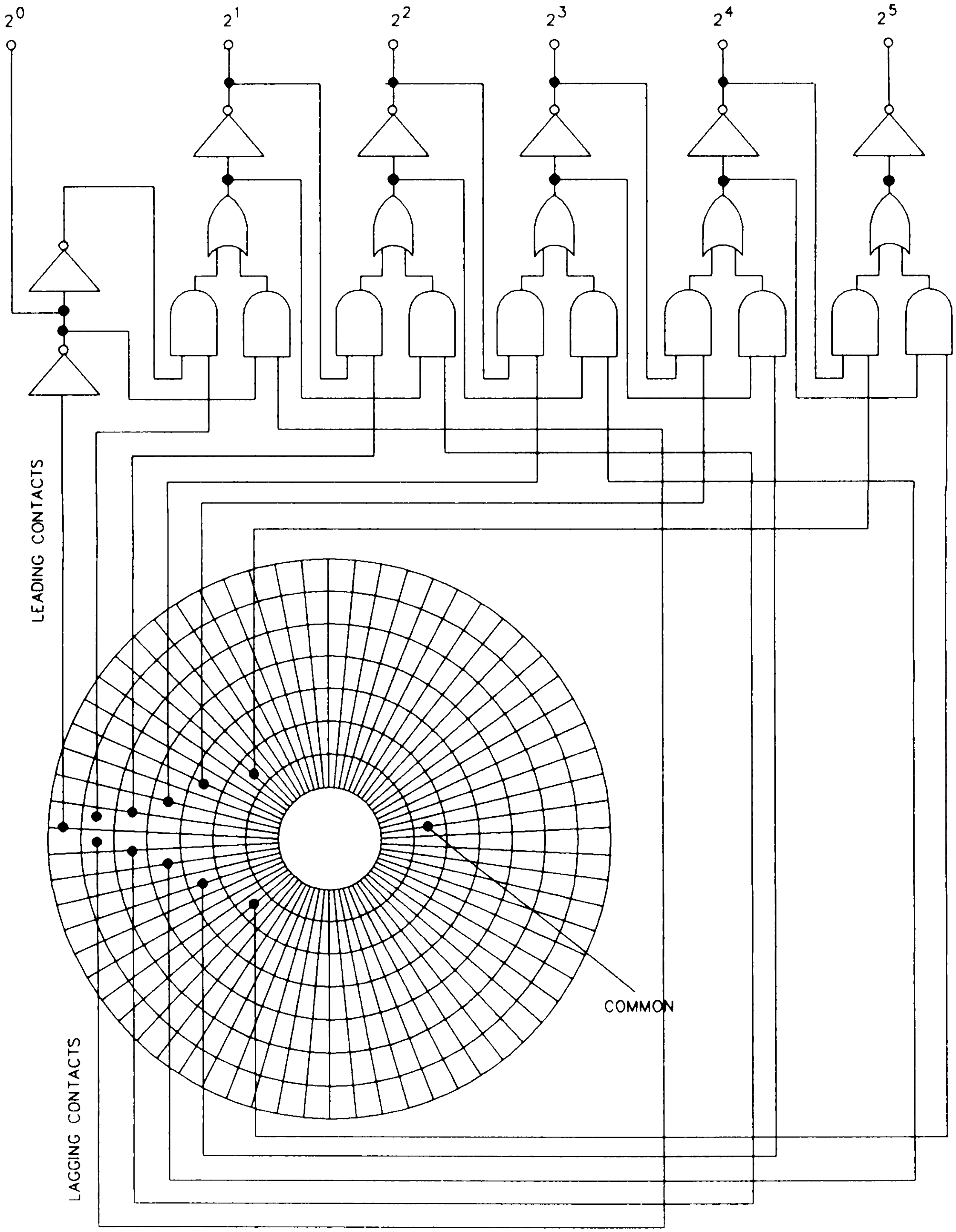


FIGURE 55. V-scan.

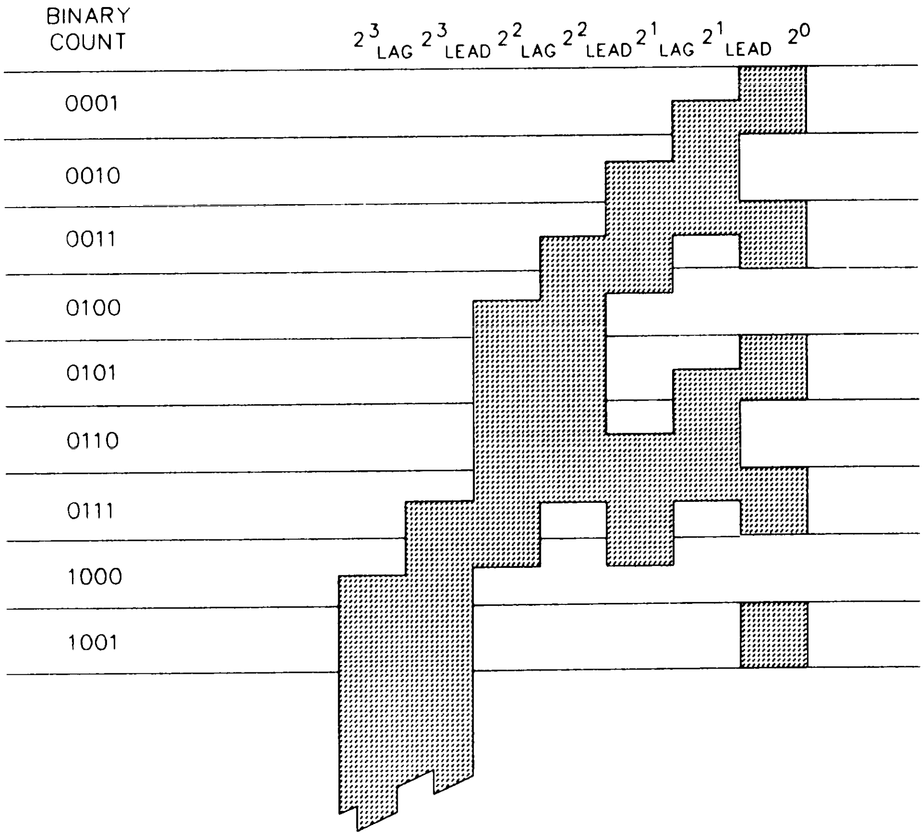


FIGURE 56. V-scan variation with separate lead and lag tracks.

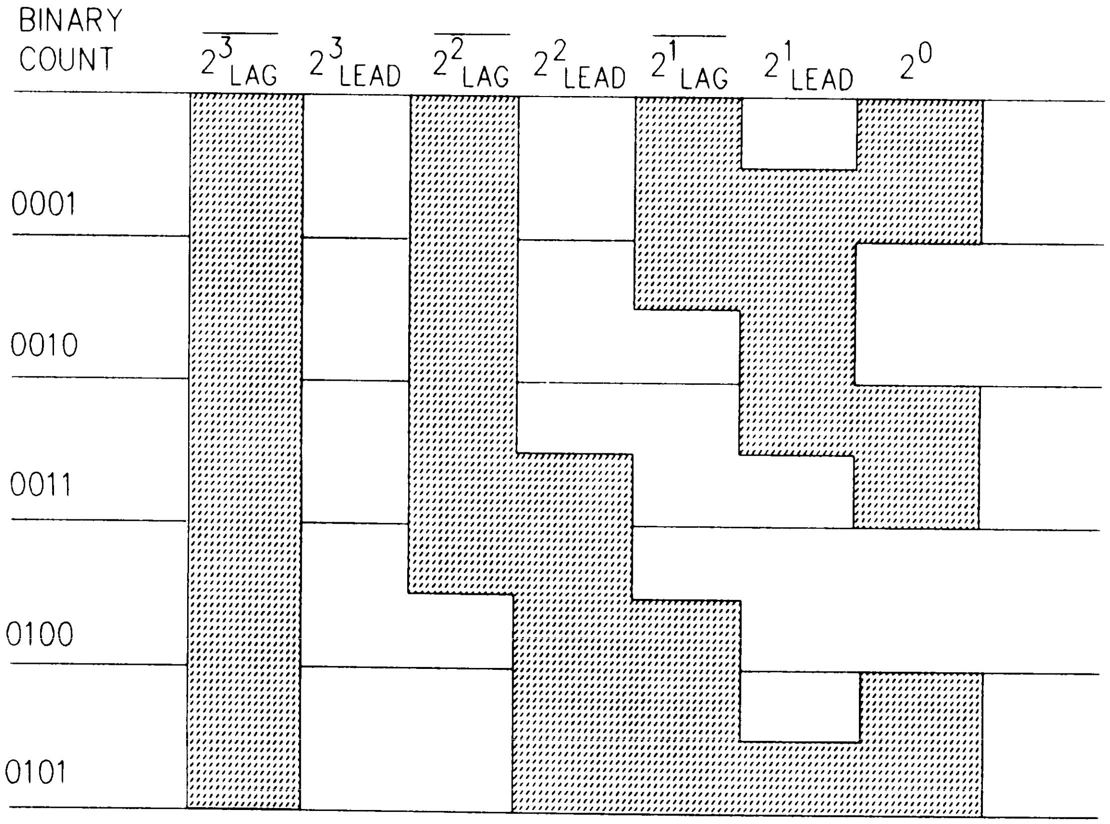


FIGURE 57. M-scan.

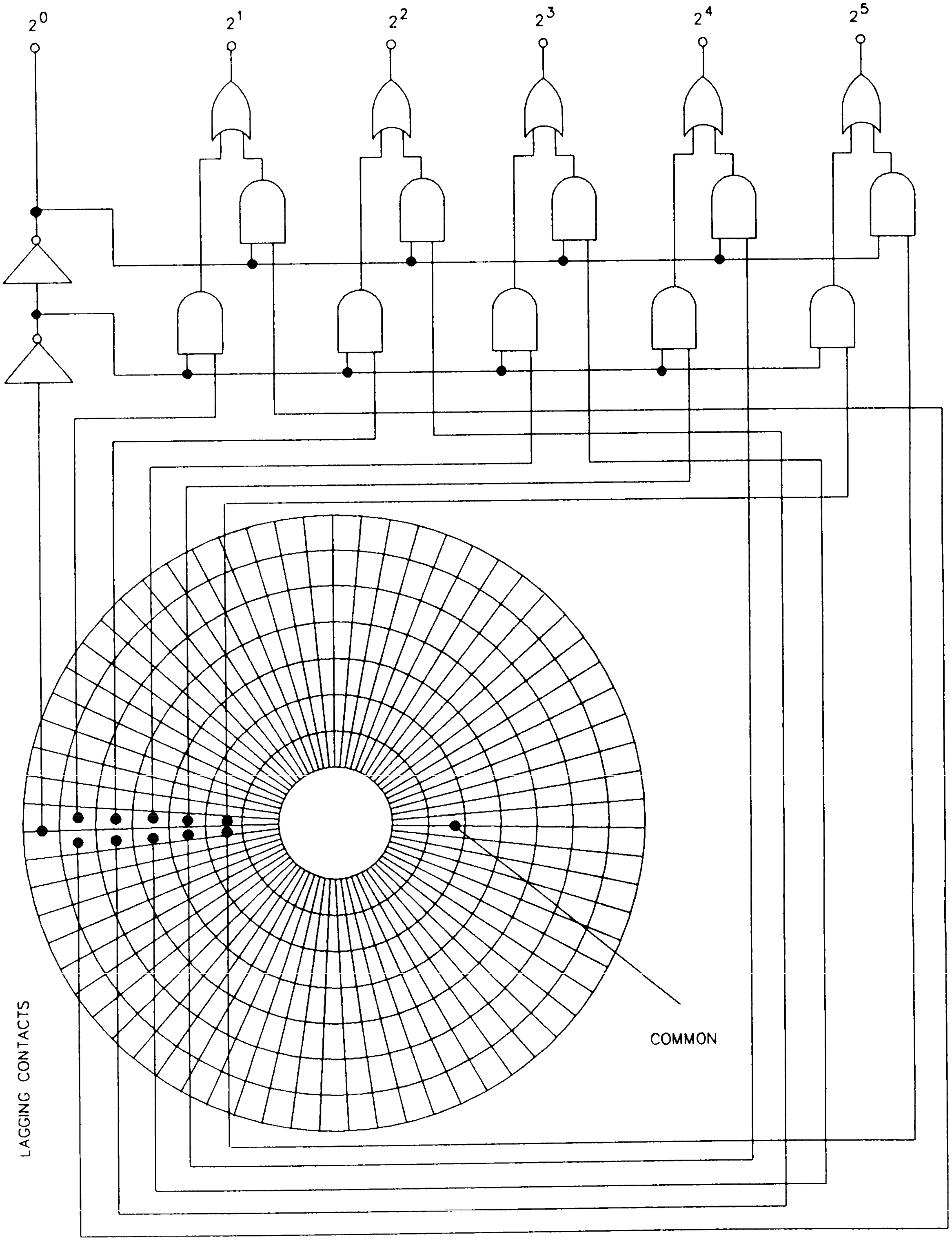


FIGURE 58. U-scan.

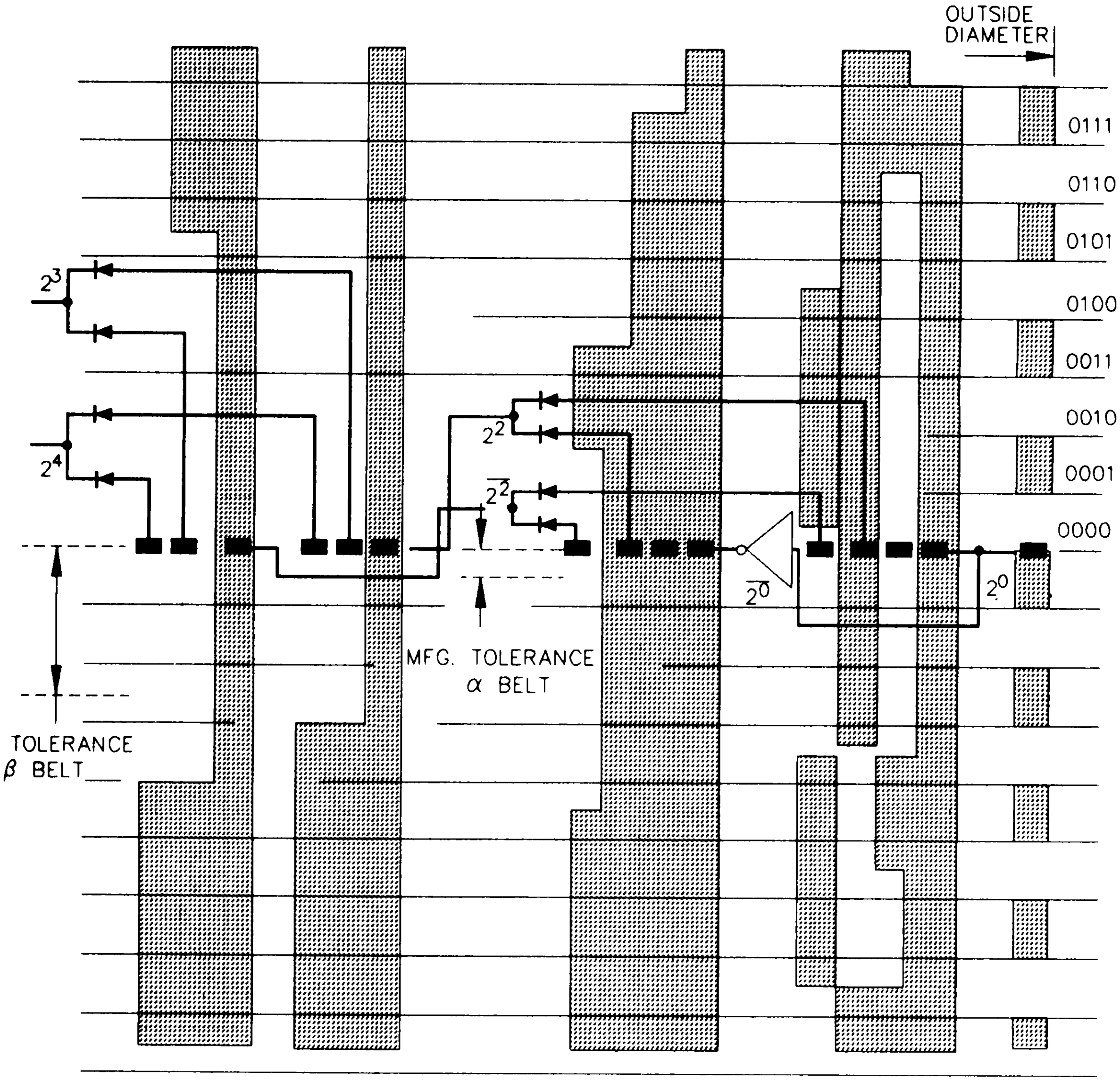


FIGURE 59. Two-belt U-scan switching scheme.

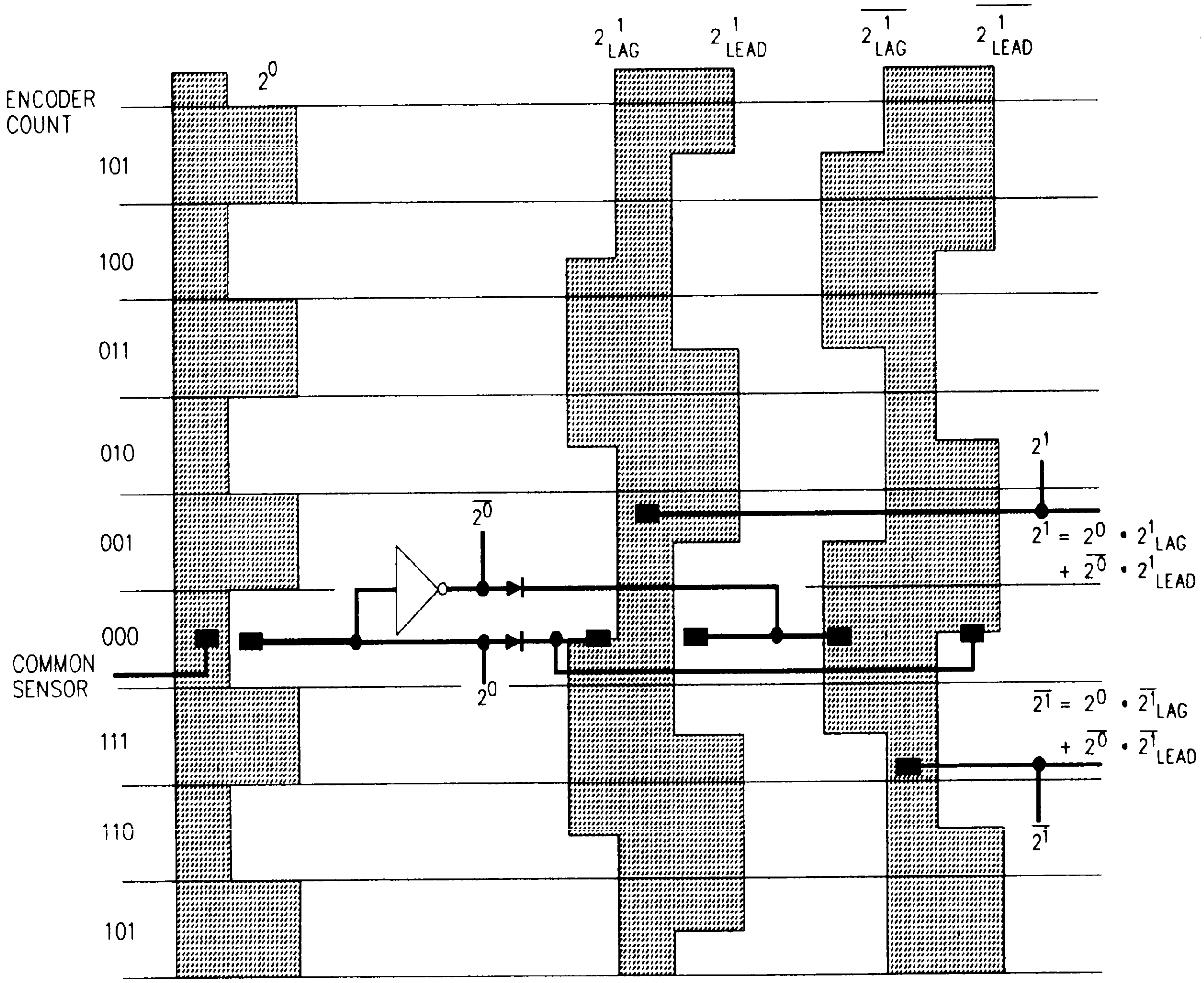


FIGURE 60. Typical self-selecting V-scan.

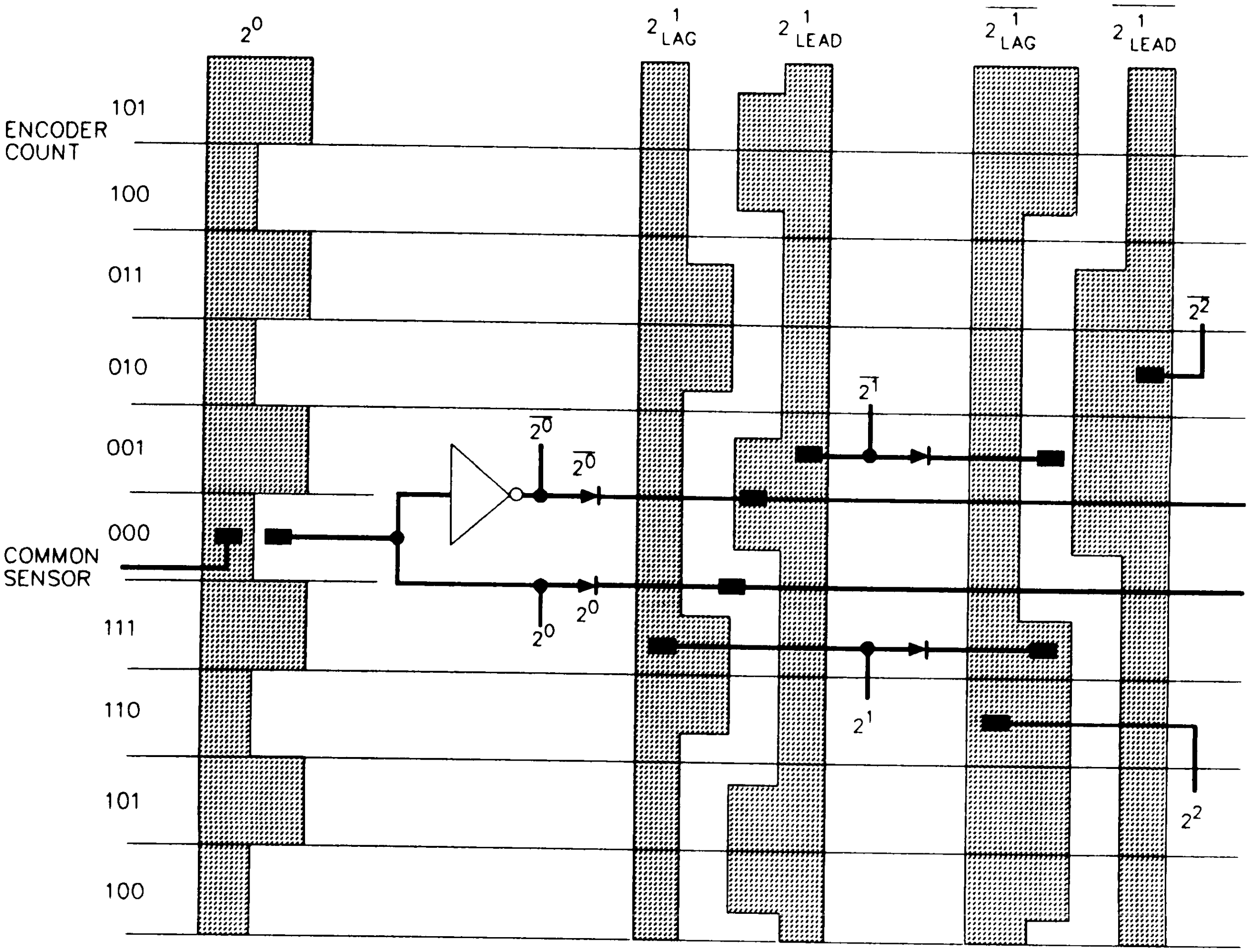


FIGURE 61. Self-selecting V-scan with staggered arrangement of sensors.

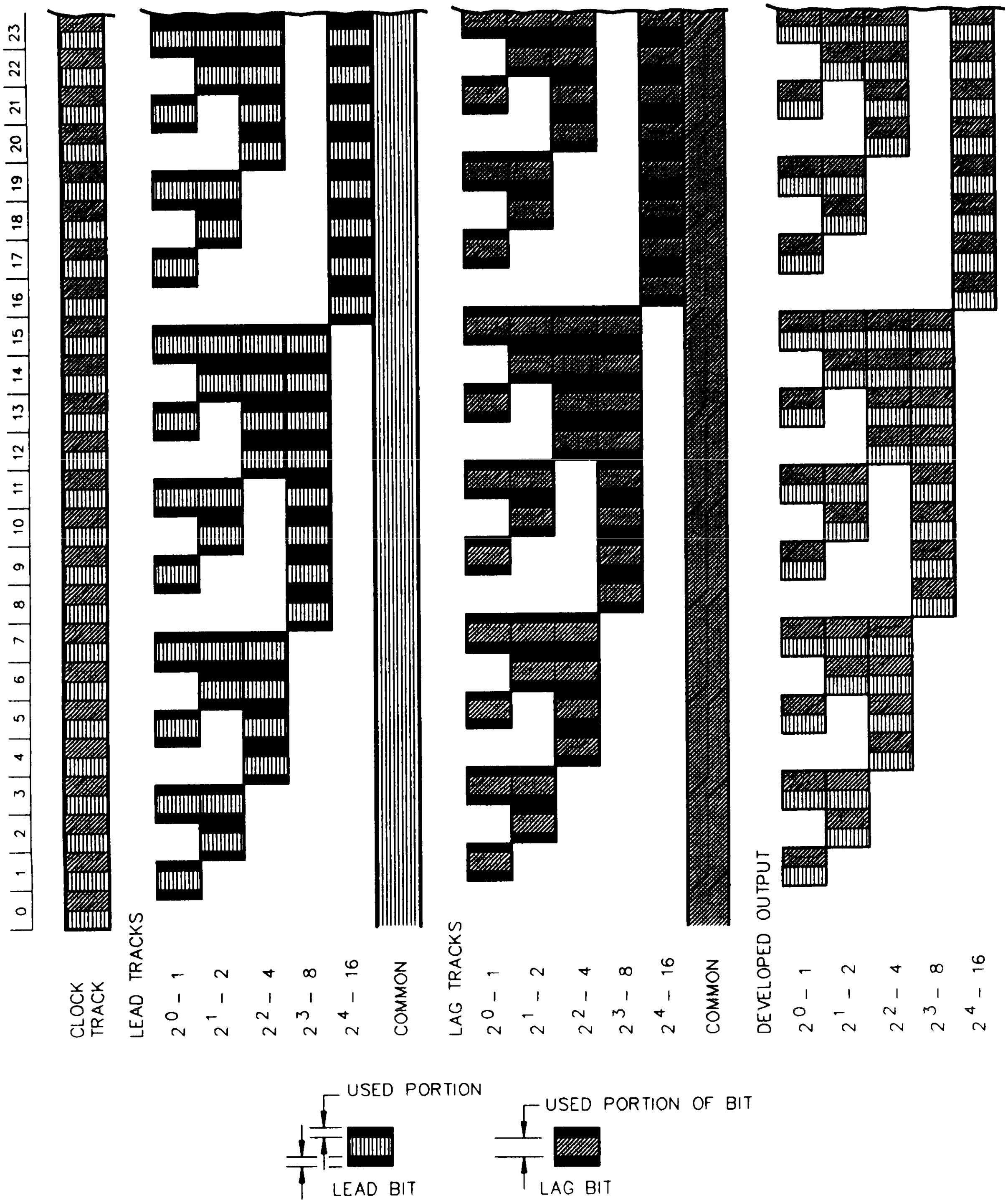


FIGURE 62. Self-selecting U-scan.

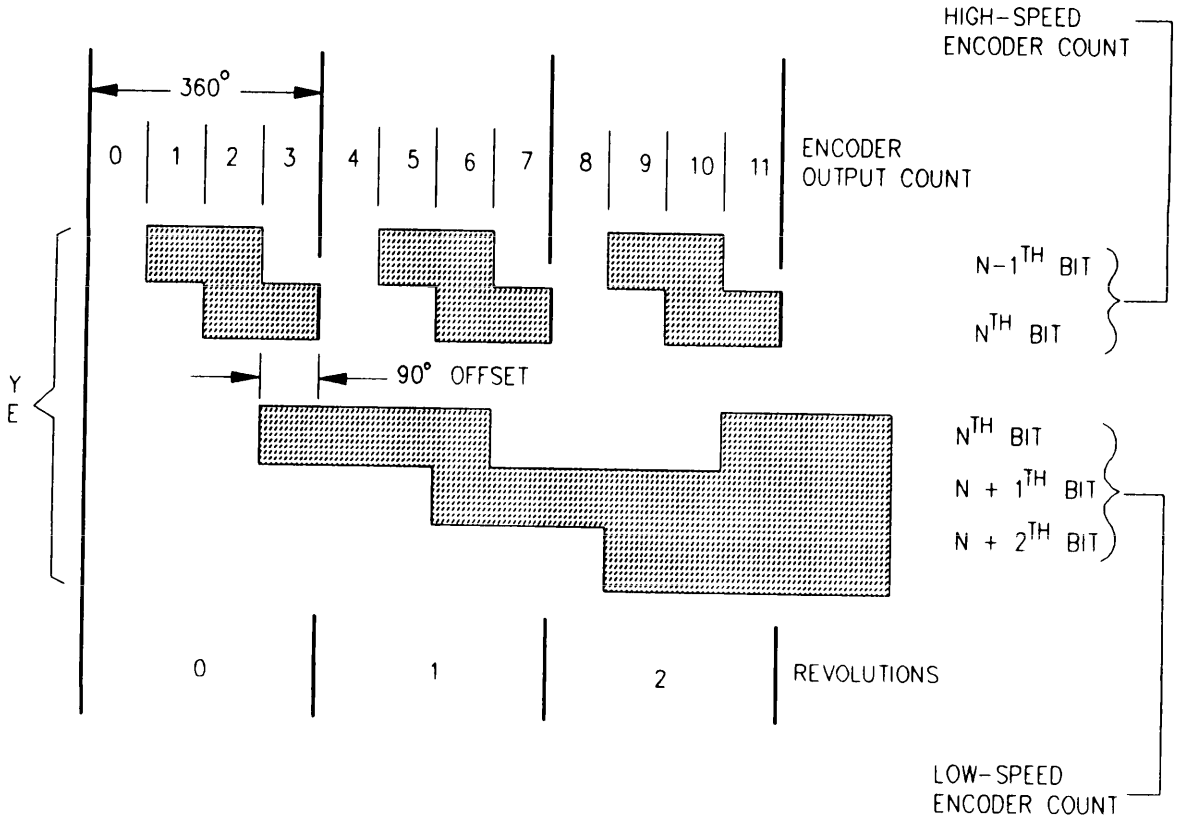


FIGURE 63. Typical logic scheme for a multi-turn encoder.

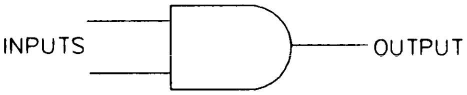
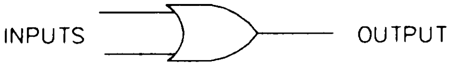
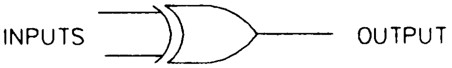
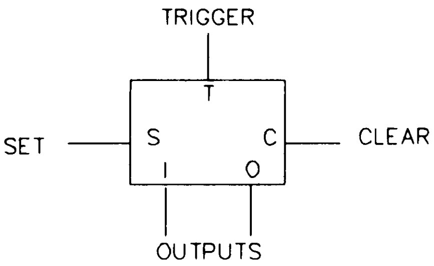
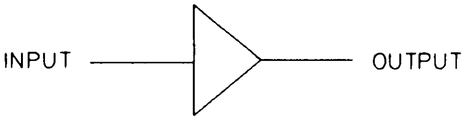
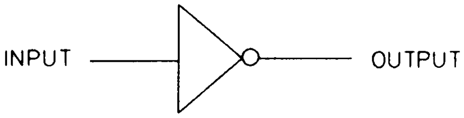
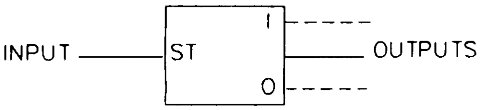
SYMBOL	NOMENCLATURE	FUNCTION
	AND GATE	GENERATES AN OUTPUT IF, AND ONLY IF, ALL INPUTS ARE PRESENT.
	DIODE	CONDUCTS IN ONE DIRECTION ONLY. USED FOR GATING OR ISOLATION OF ENCODER SIGNALS.
	INCLUSIVE OR GATE	GENERATES AN OUTPUT IF, AND ONLY IF, ONE OR MORE INPUTS ARE PRESENT.
	EXCLUSIVE OR GATE	GENERATES AN OUTPUT IF, AND ONLY IF, ONE INPUT IS PRESENT.
	FLIP-FLOP	STORAGE DEVICE FOR ONE BIT OF INFORMATION.
	AMPLIFIER	LEVEL CHANGER, ISOLATION DEVICE, OPERATIONAL AMPLIFIER
	AMPLIFIER	INVERTER
	SCHMITT TRIGGER	GENERATES AN OUTPUT WHEN THE INPUT EXCEEDS PRESENT THRESHOLD (LEVEL).

FIGURE 64. Selected graphic logic symbols and functions.

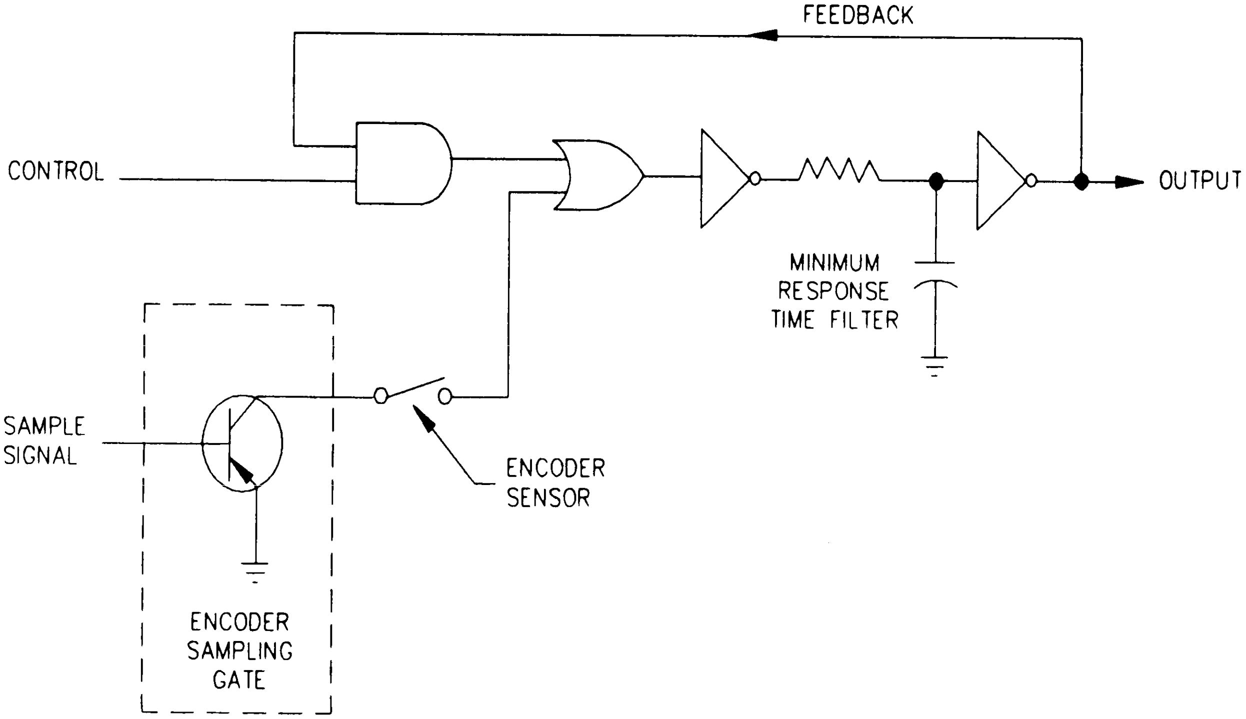
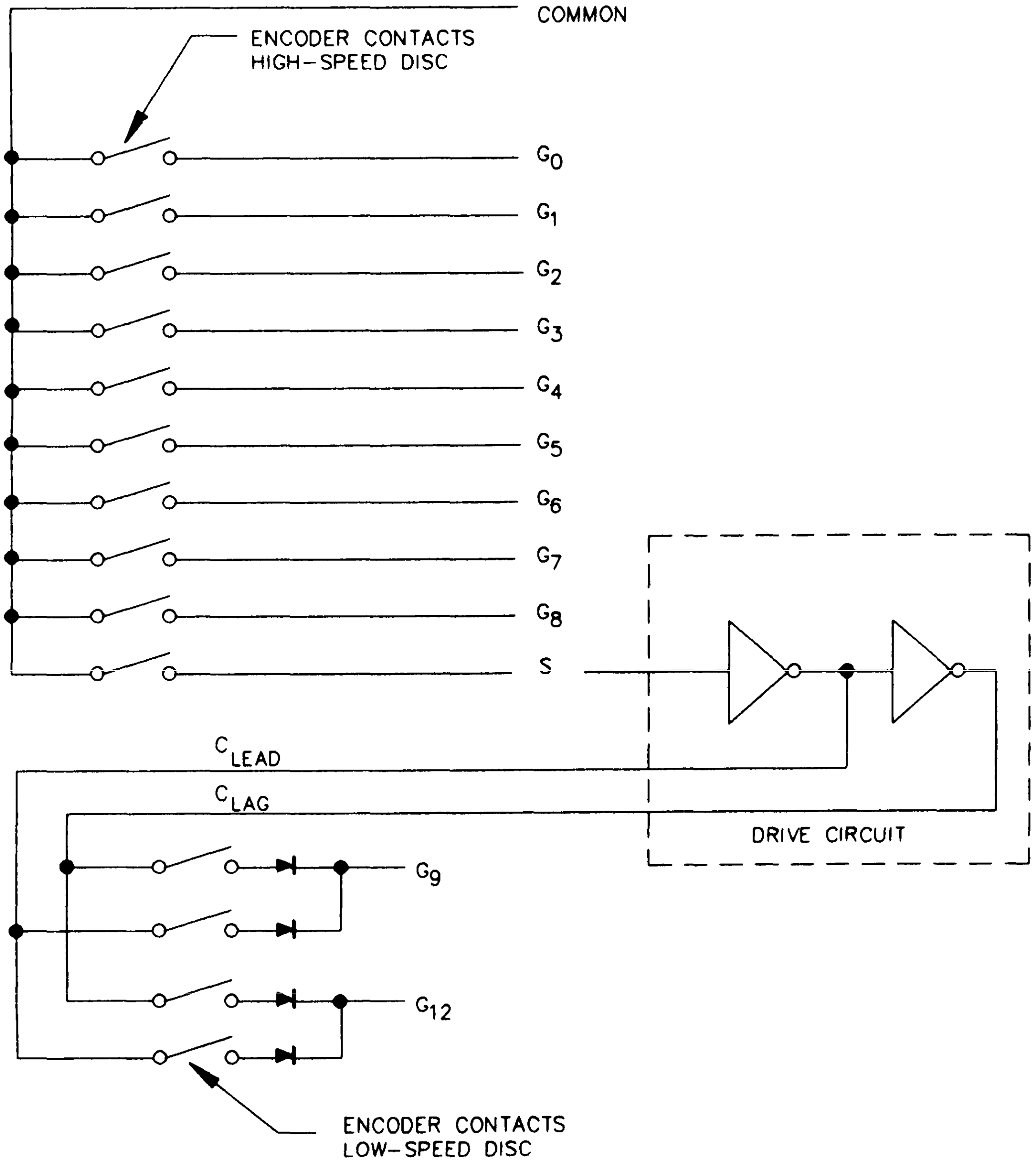


FIGURE 65. Typical latch circuit.



NOTE:

1. DRIVE CIRCUIT MUST BE DESIGNED SO THAT WHEN S BIT CHANGES STATE, BOTH OUTPU
(C_{LEAD} AND C_{LAG}) MUST BE TRUE (THAT IS, BOTH COMMONS MUST BE ENERGIZED).

FIGURE 66. Typical 13-bit, multi-turn geared gray code encoder.

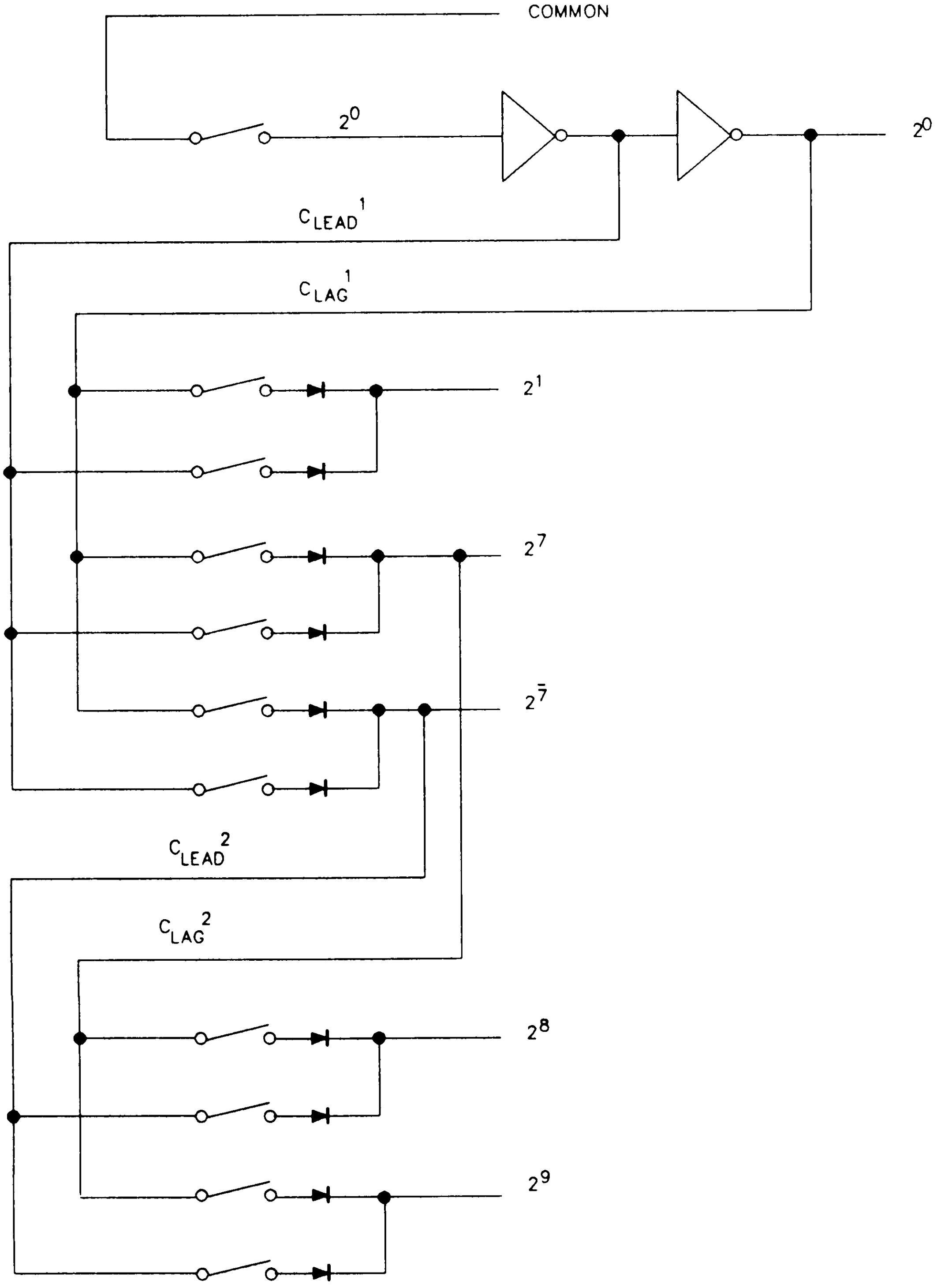
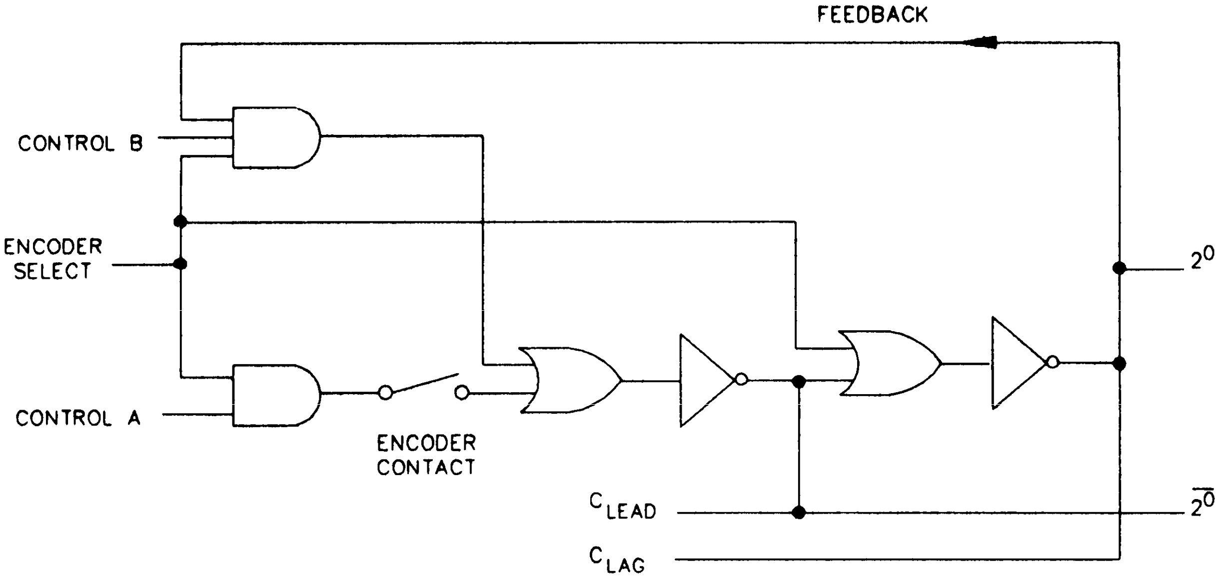


FIGURE 67. Typical U-scan, natural binary encoder.



TRUTH TABLE

	CONTROL A	CONTROL B	ENCODER SELECT
FOLLOW	1	0	1
LATCH	1	1	1
STORE	0	1	1
INHIBIT	1 + 0	1 + 0	0

FIGURE 68. Follow-latch-store network.

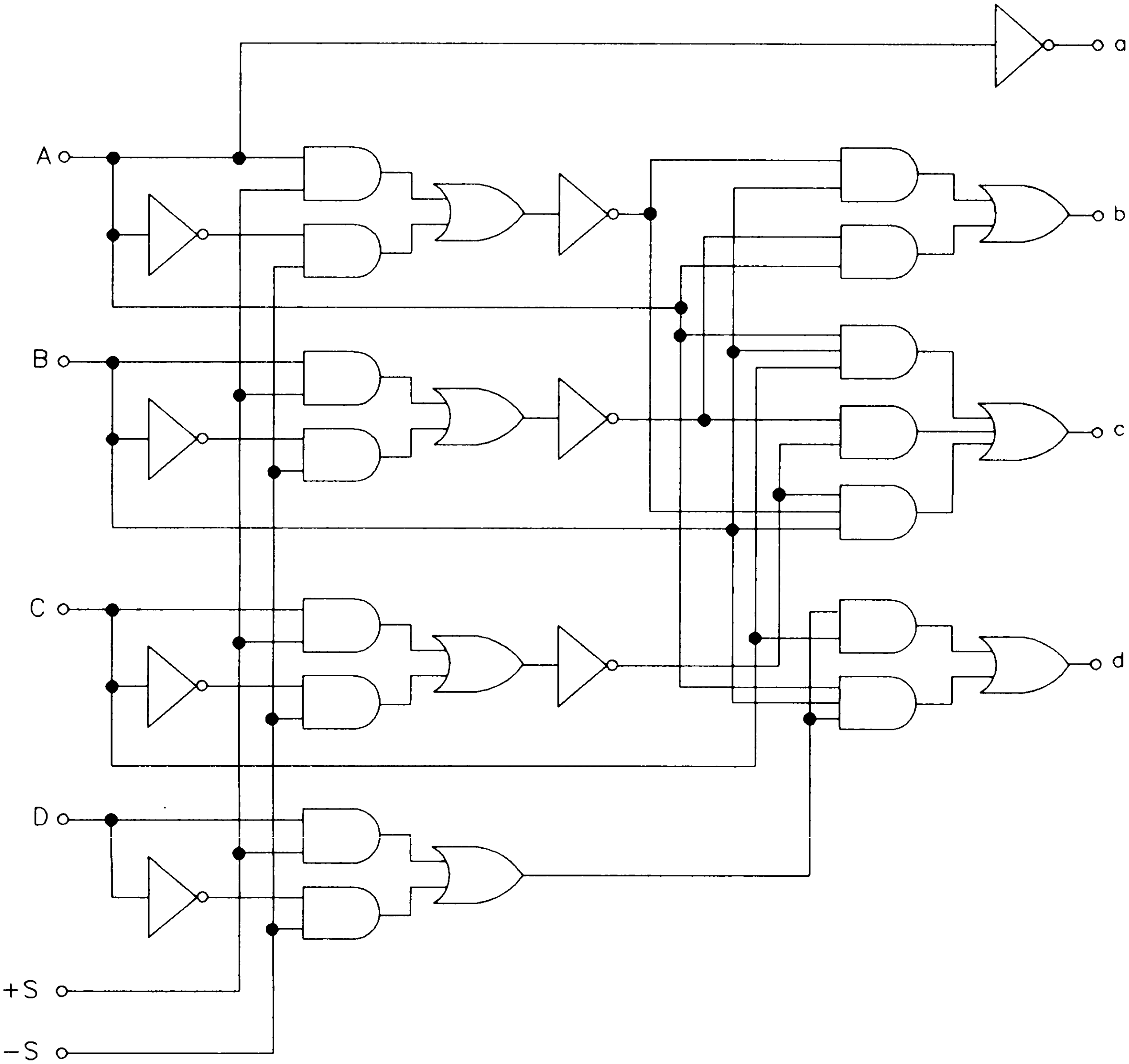


FIGURE 69. Excss-3 to natural binary conversion network.

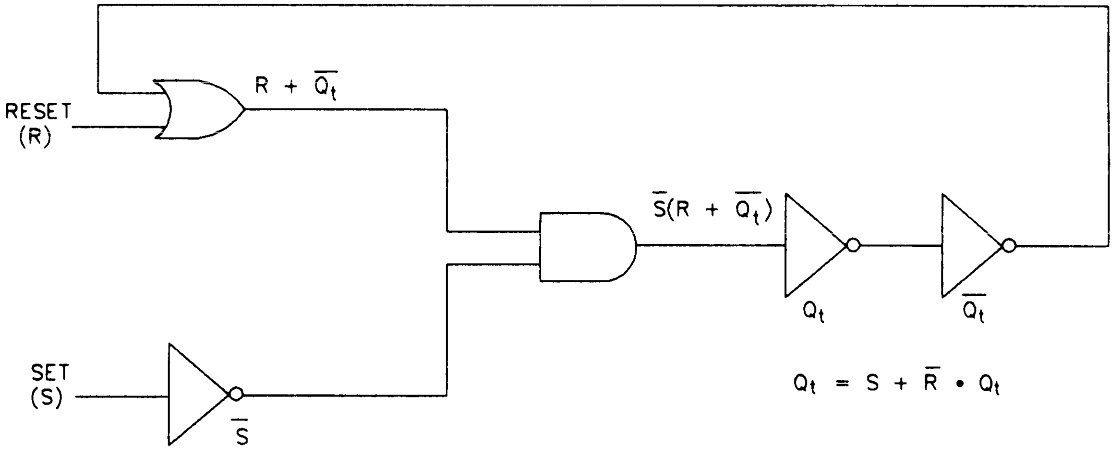
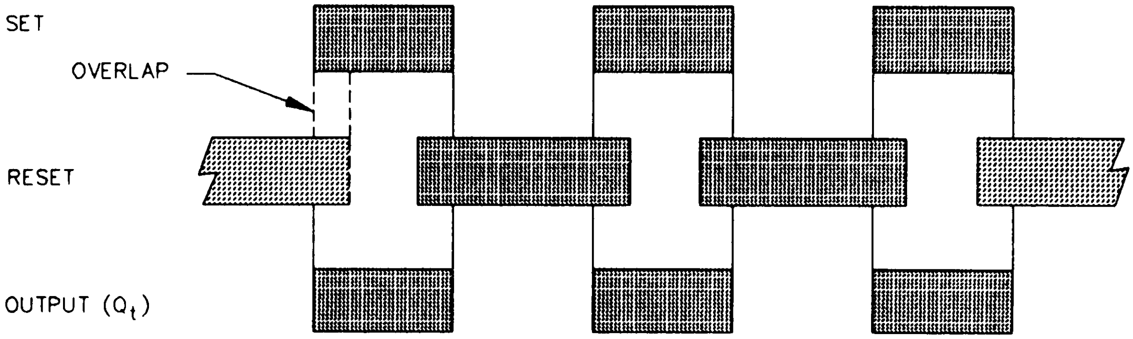


FIGURE 70. Basic logic for set-reset selector circuit.



NOTE:

1. SOLID SECTIONS INDICATE ON (TRUE).

FIGURE 71. Set-reset selector circuit timing relationship.

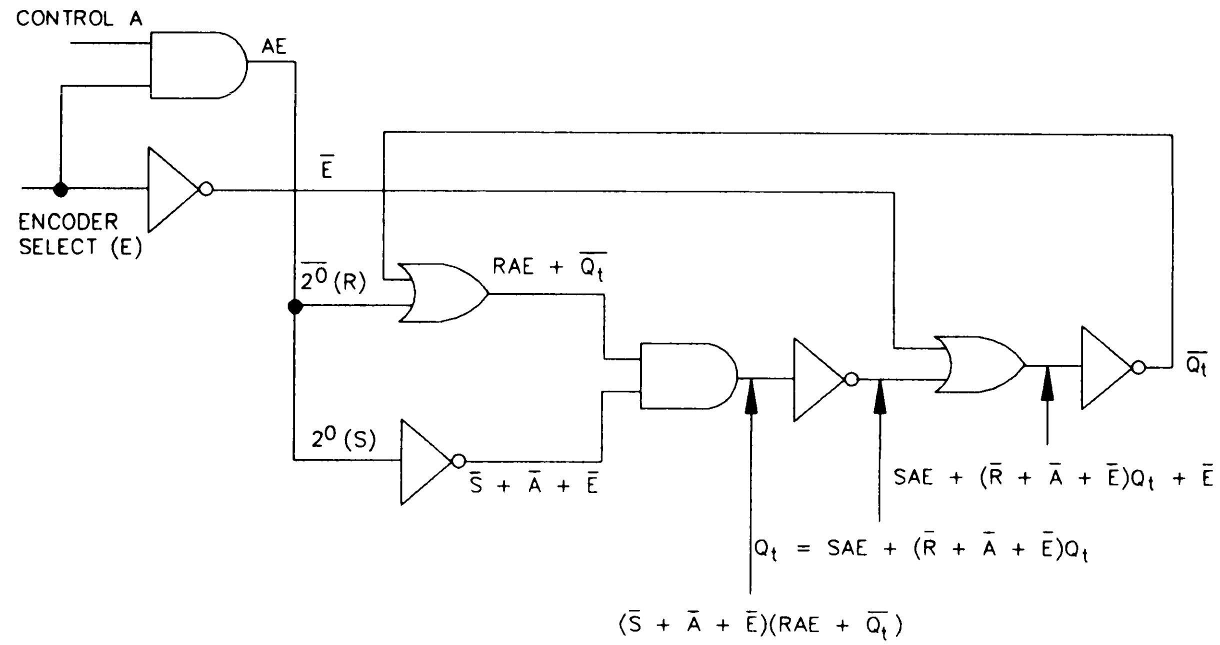
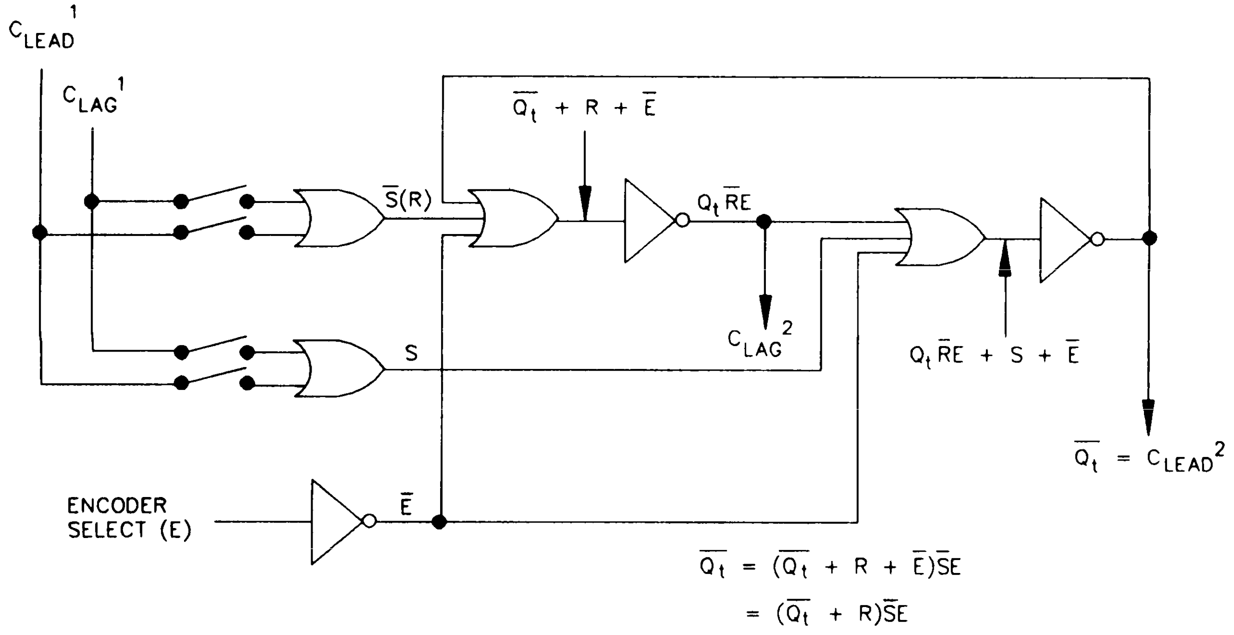


FIGURE 72. Set-reset selector circuit with control logic.



NOTE:

1. S AND $\overline{S}$(R) CANNOT BOTH BE TRUE. HOWEVER, DUE TO NOISE, BOTH CAN BE FALSE. THE PURPOSE OF THE SET-RESET CIRCUIT IS TO STORE PREVIOUS VALUE OF OUTPUT IN THE EVENT $\overline{S}$(R) AND S ARE FALSE.

FIGURE 73. Set-reset inter-disc or inter-belt selector circuit.

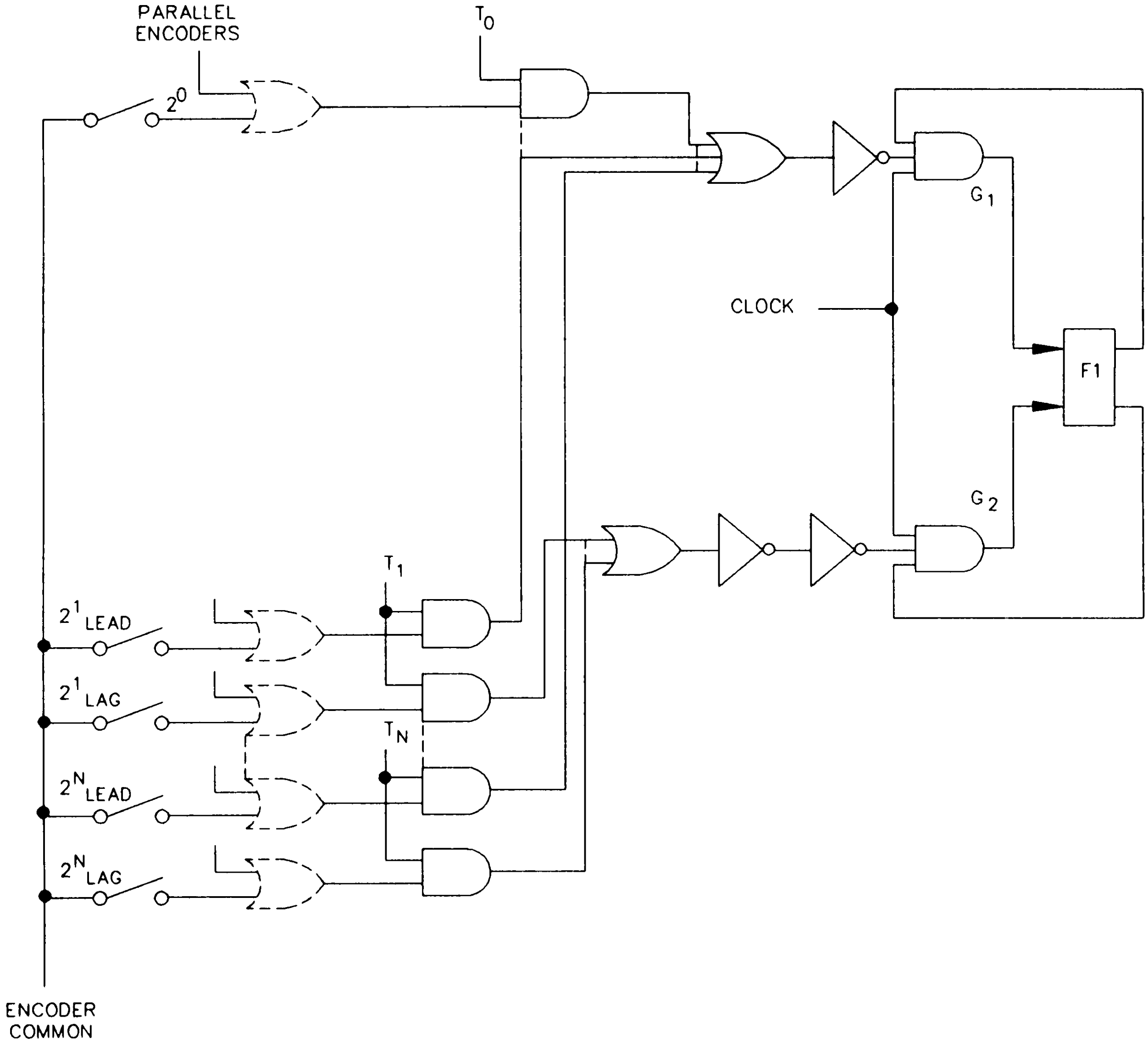


FIGURE 74. V-scan selector circuit.

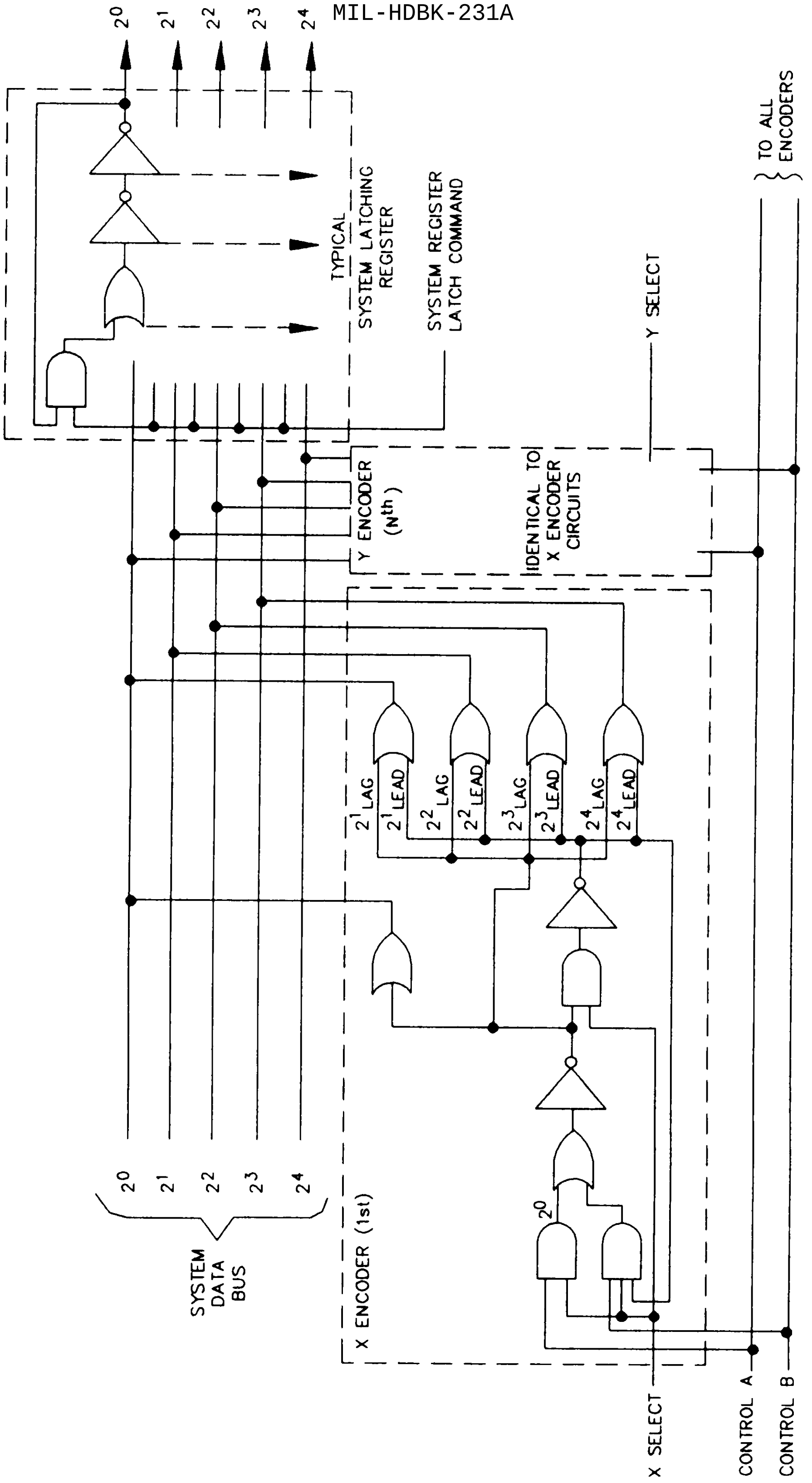


FIGURE 75. <u>High reliability logic system.</u>

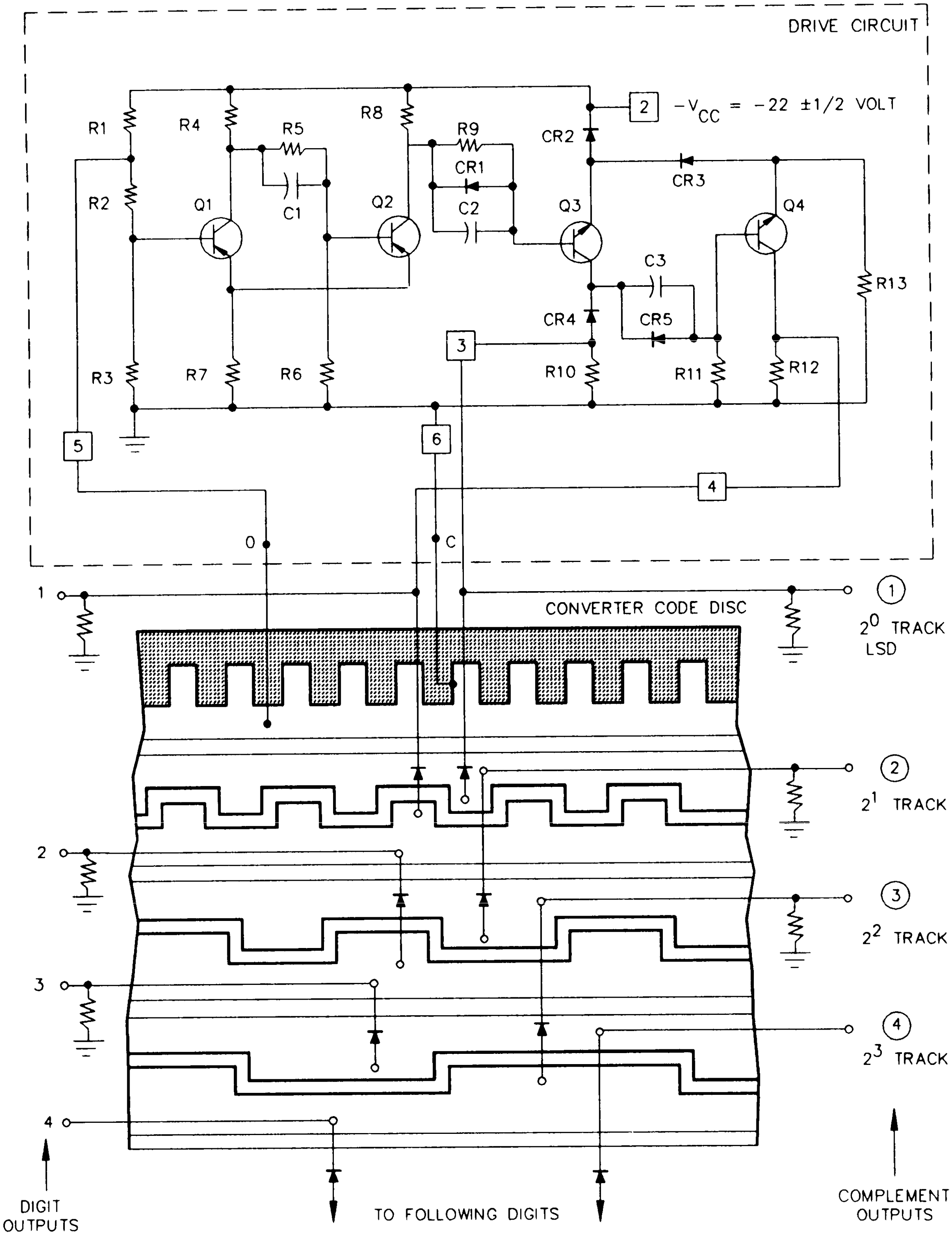


FIGURE 76. External driver circuit module - negative interrogation.

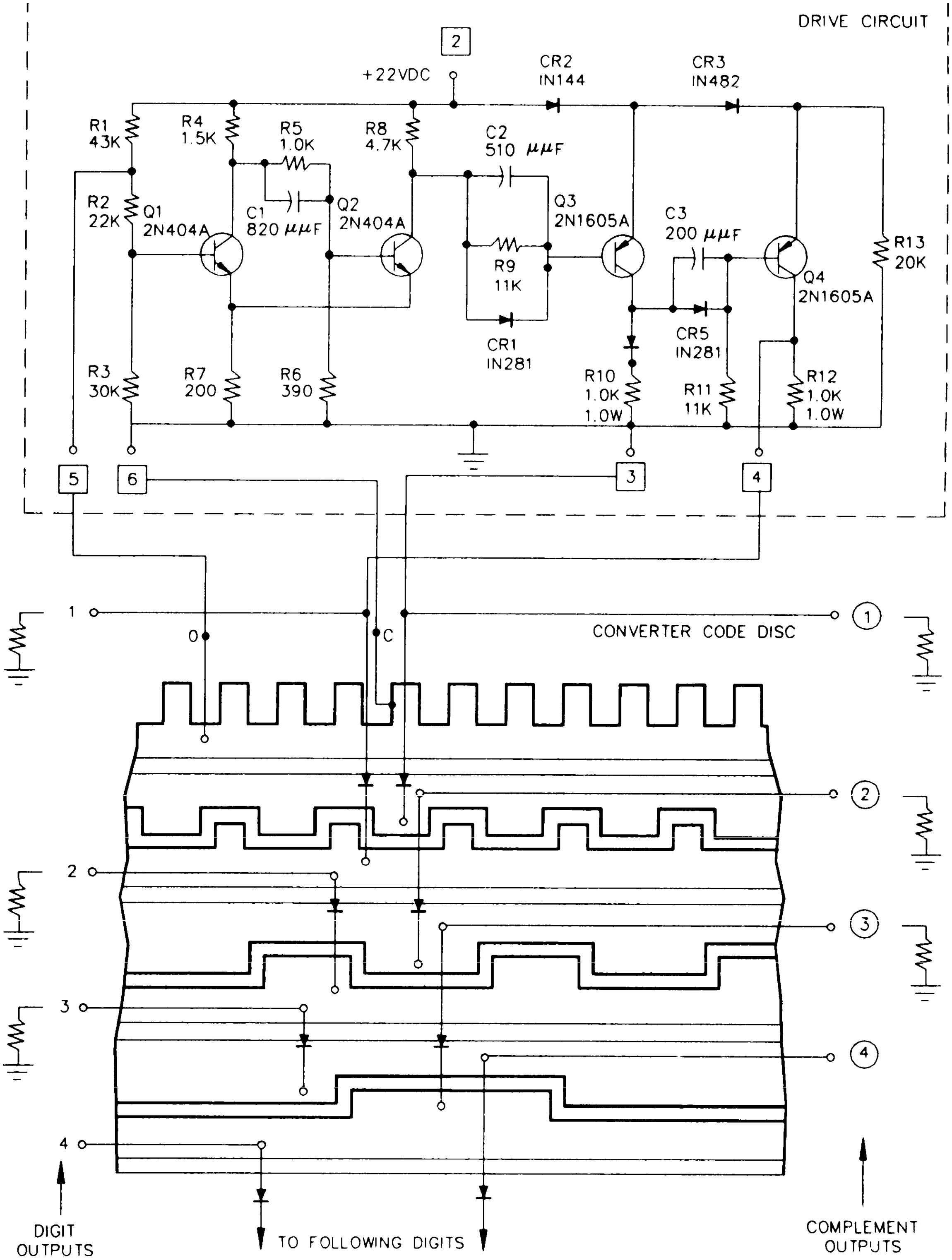


FIGURE 77. External driver circuit module - positive interrogation.

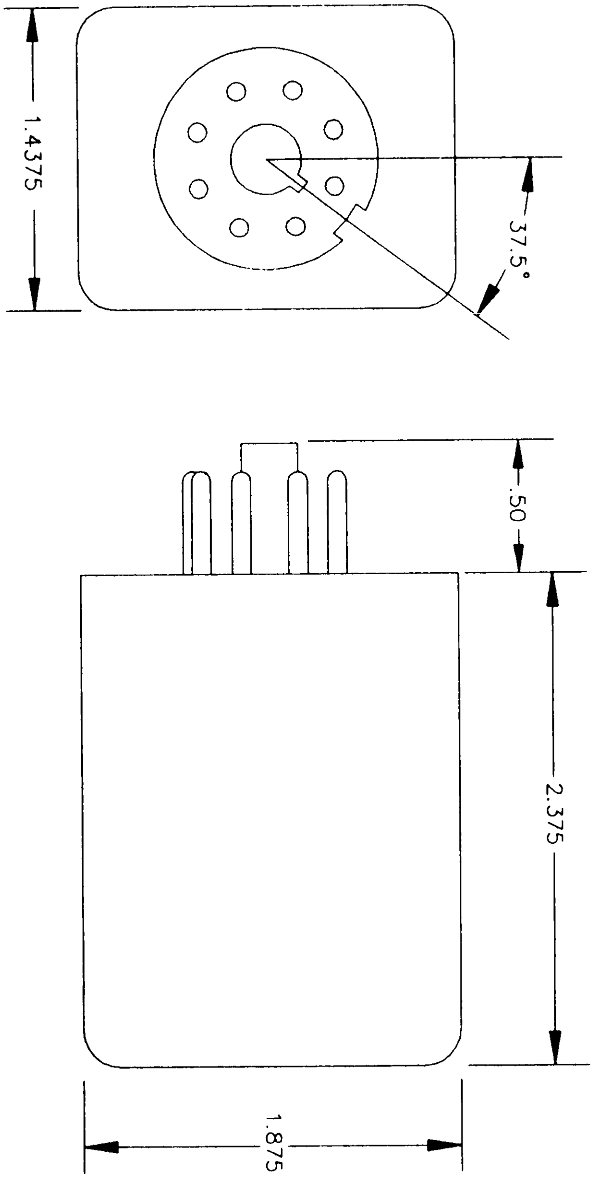
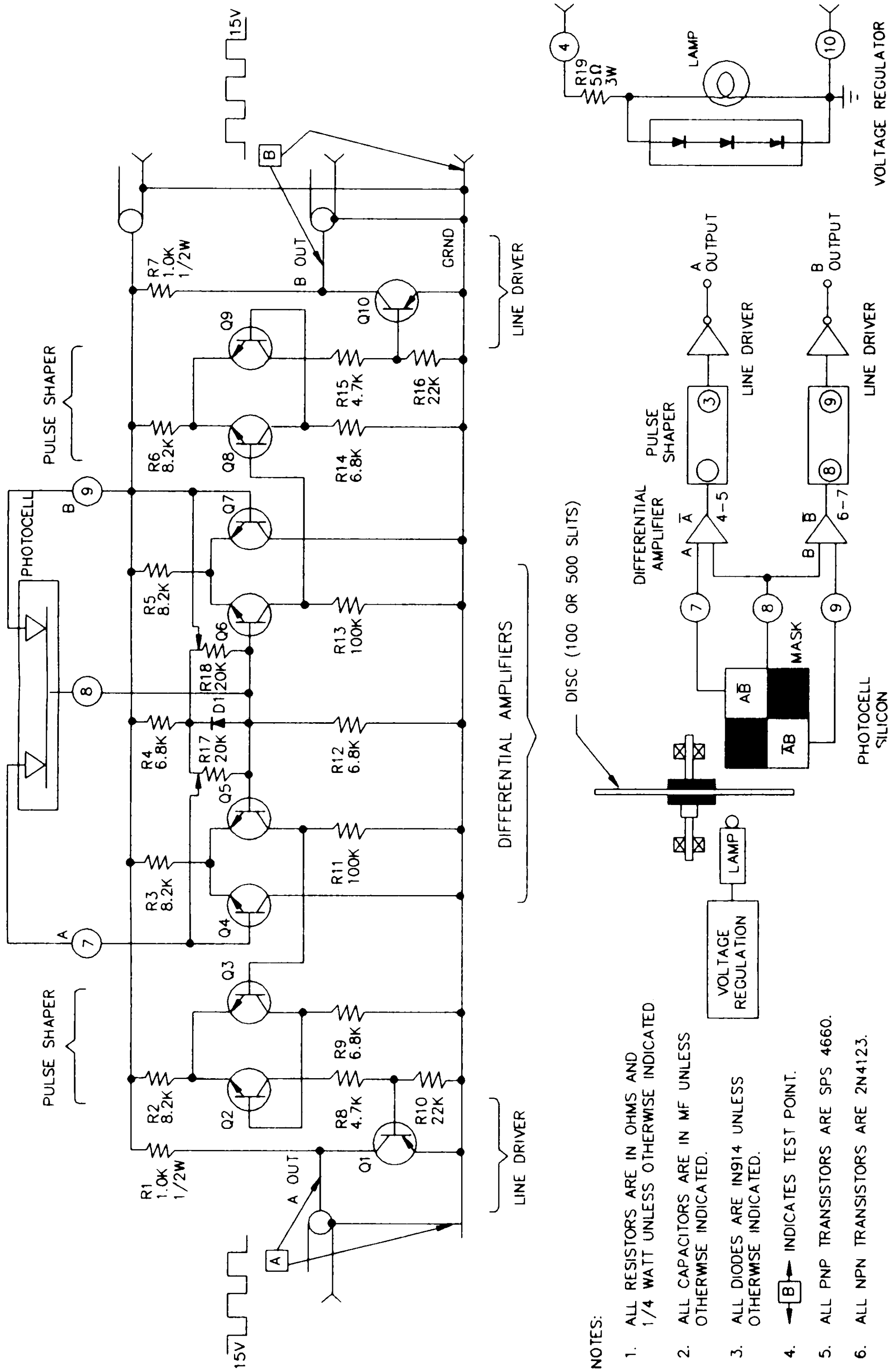


FIGURE 78. Typical external driver circuit packaging.



NOTES:

1. ALL RESISTORS ARE IN OHMS AND 1/4 WATT UNLESS OTHERWISE INDICATED.
2. ALL CAPACITORS ARE IN MF UNLESS OTHERWISE INDICATED.
3. ALL DIODES ARE IN914 UNLESS OTHERWISE INDICATED.
4. ◄B► INDICATES TEST POINT.
5. ALL PNP TRANSISTORS ARE SPS 4660.
6. ALL NPN TRANSISTORS ARE 2N4123.

FIGURE 79. Integral driver circuit for 2000-count optical encoder.

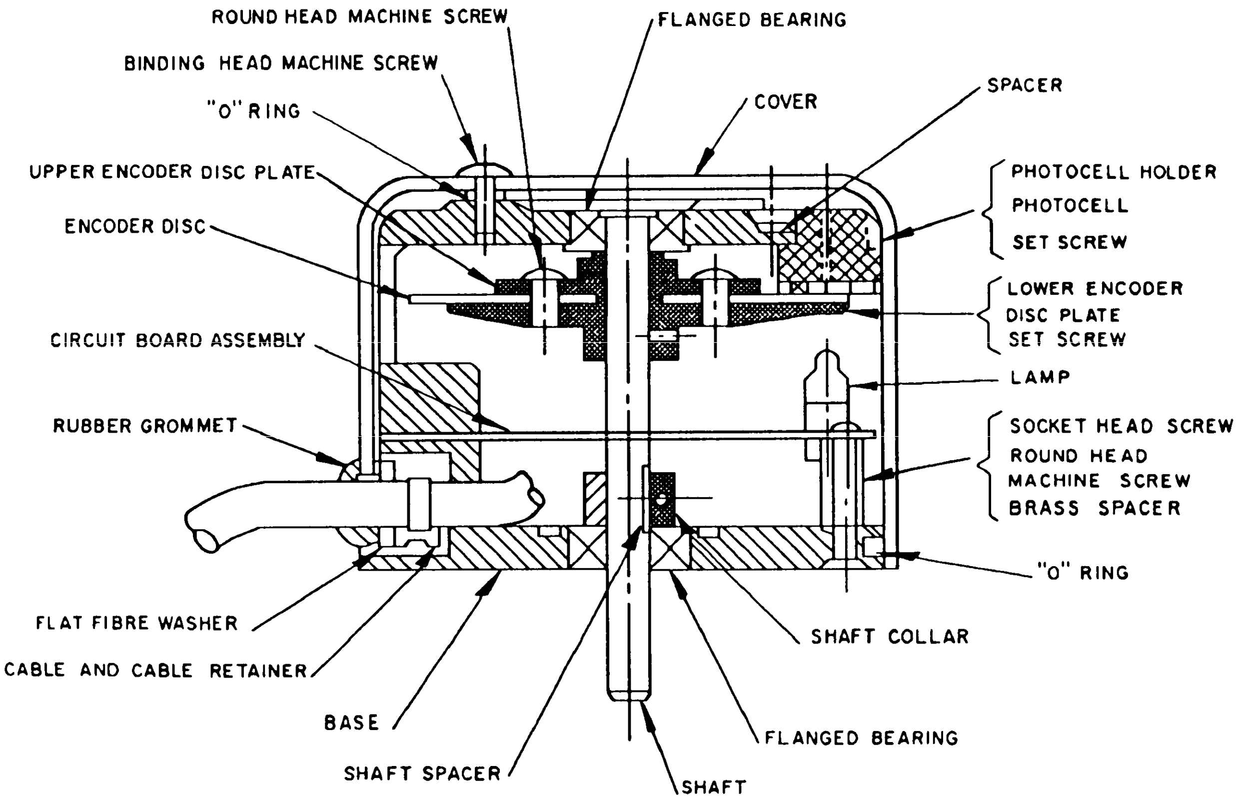


FIGURE 80. Typical integral driver circuit packaging.

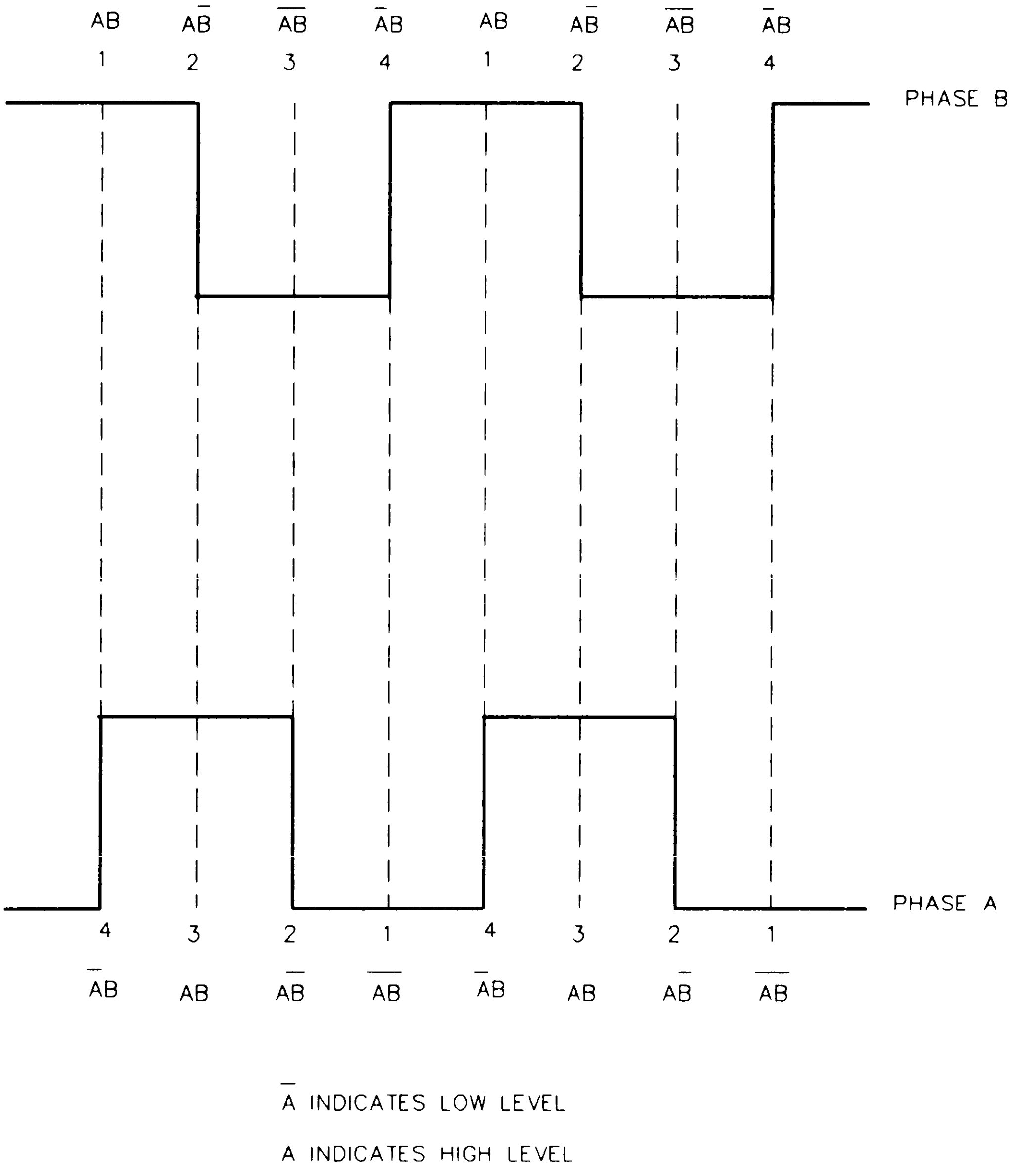


FIGURE 81. <u>Waveforms for symmetrical line driver output.</u>

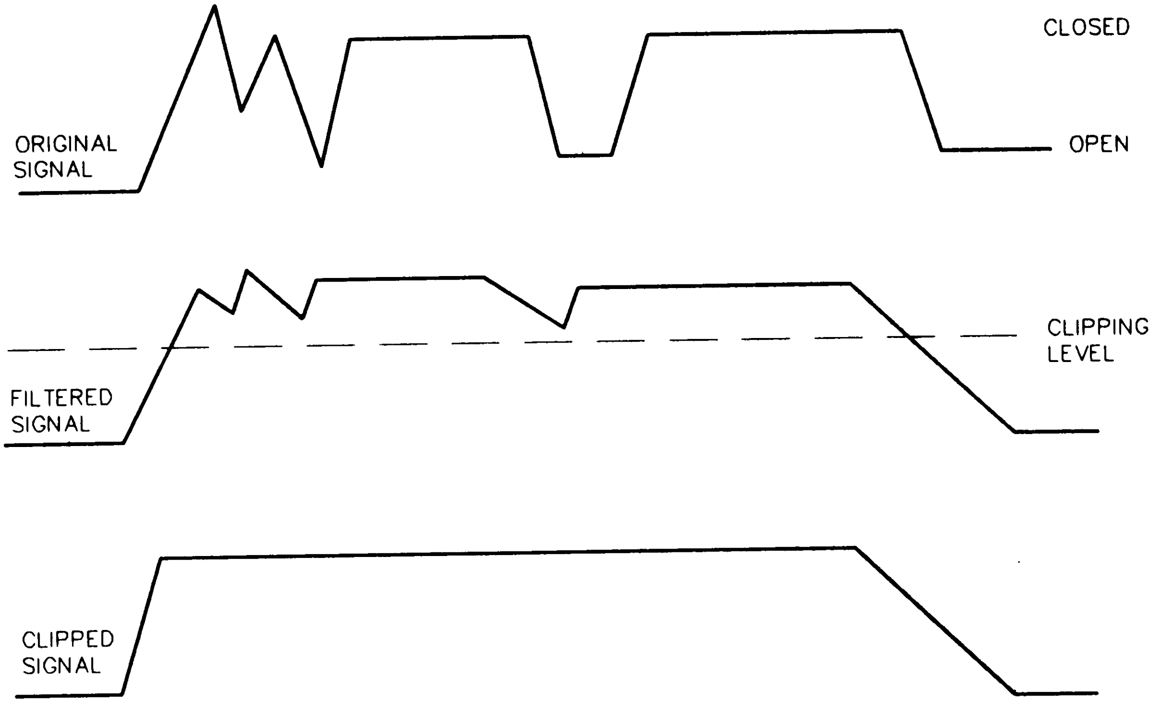


FIGURE 82. Filtering and clipping waveforms.

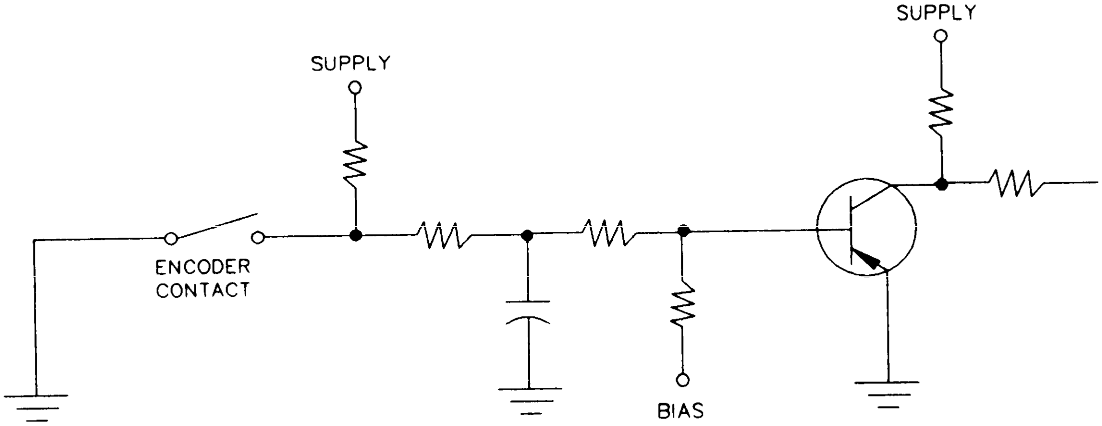


FIGURE 83. Typical filtering and clipping circuit.

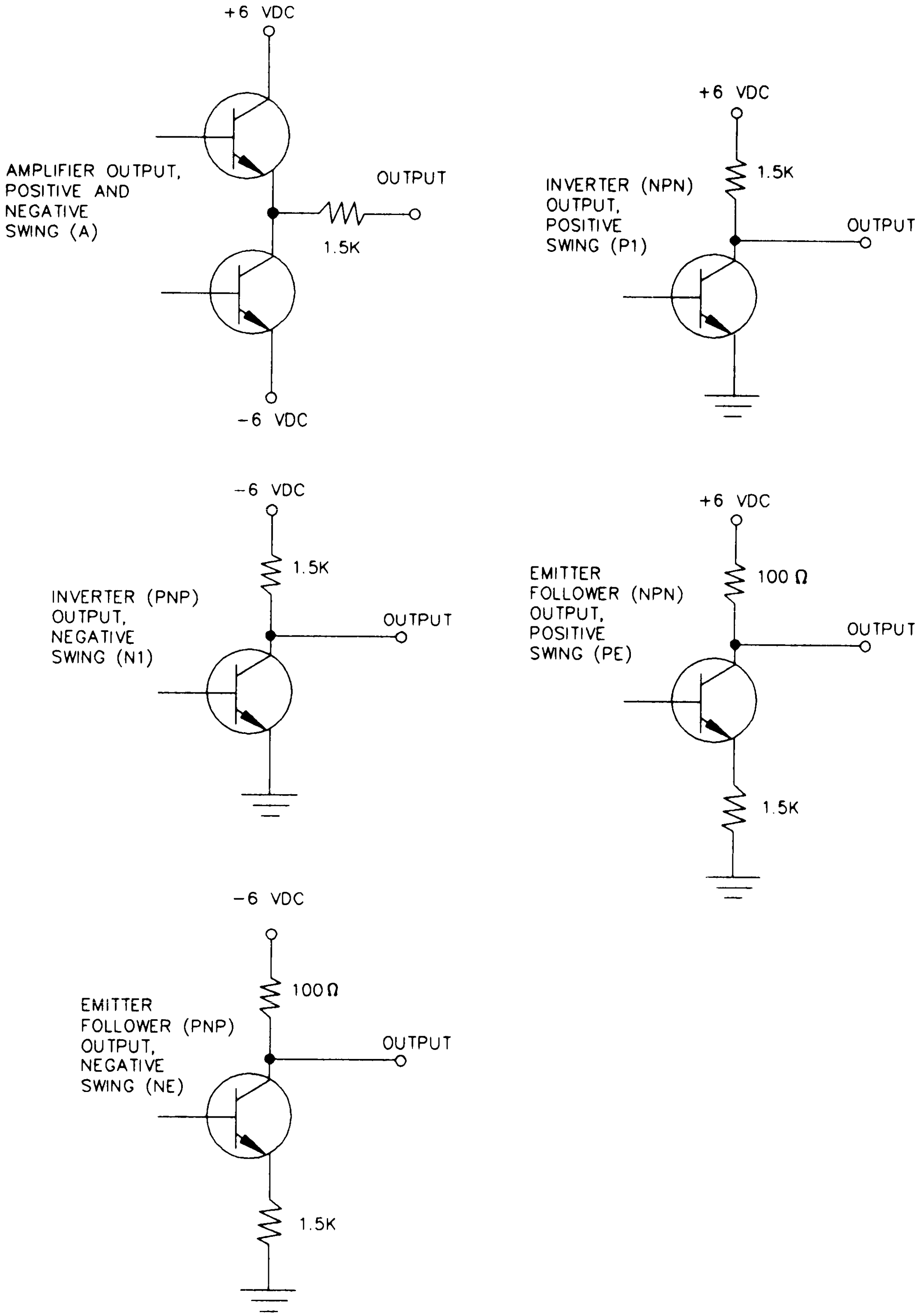


FIGURE 84. Typical output amplifier configurations.

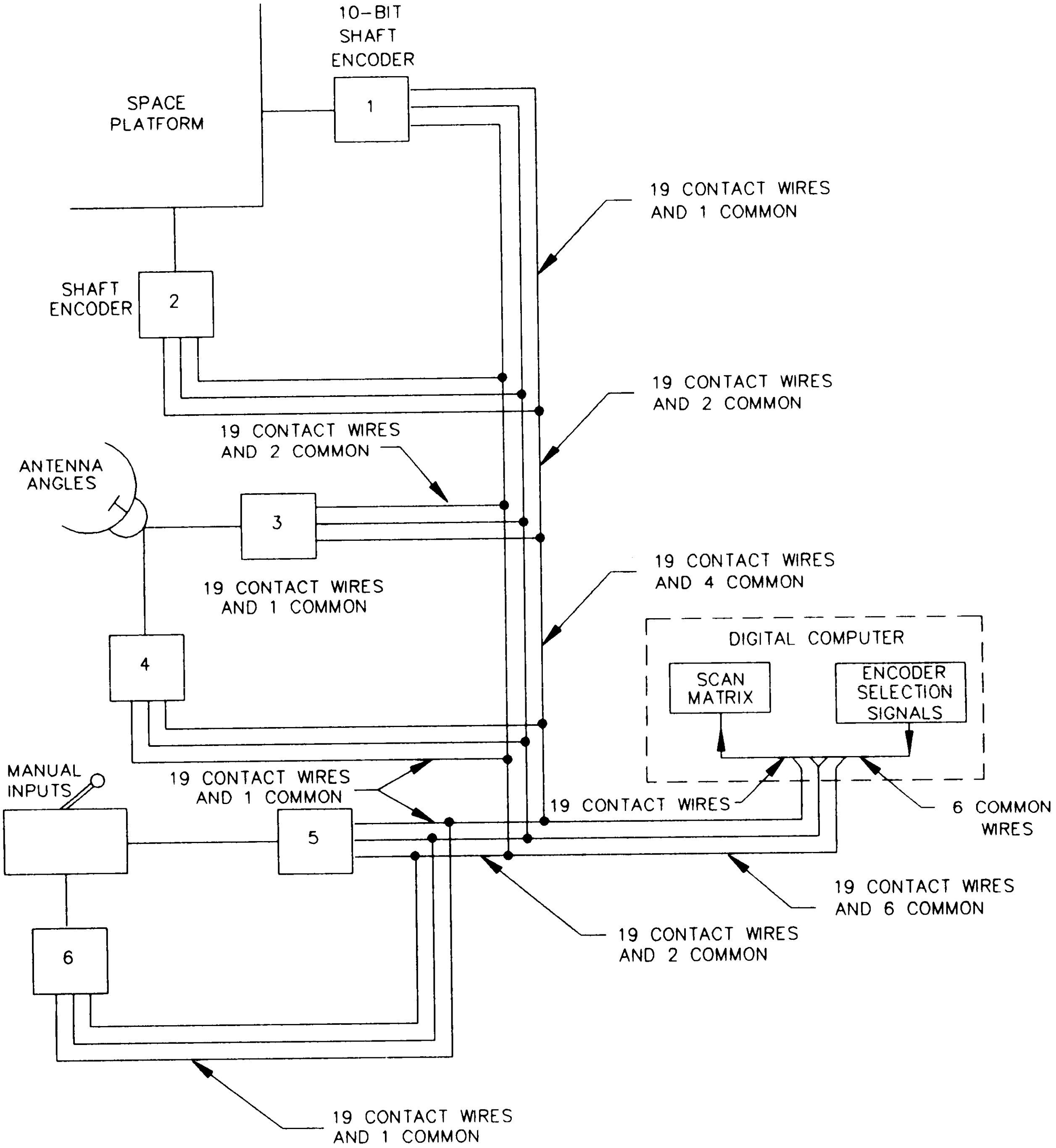
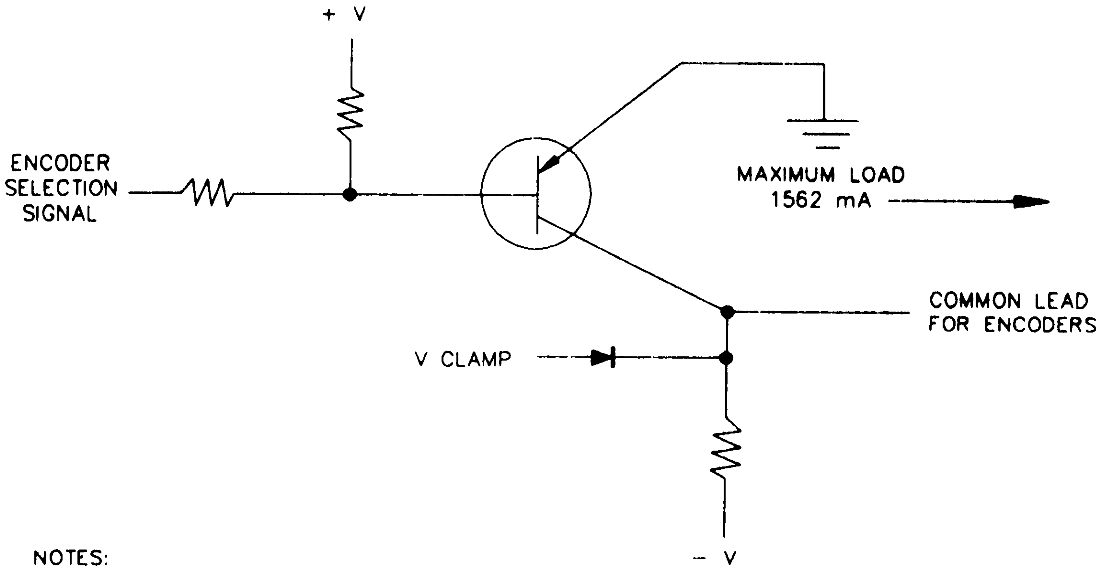


FIGURE 85. Multiple encoder system configuration.



NOTES:

1. A SUFFICIENTLY NEGATIVE VOLTAGE INPUT TURNS THE TRANSISTOR ON. ITS COLLECTOR RISES TO GROUND POTENTIAL AND THE ENCODER IS ACTIVATED.
2. ONE AMPLIFIER REQUIRED FOR EACH ENCODER FOR A TIME-SHARED MATRIX.

FIGURE 86. Grounded emitter output circuit.

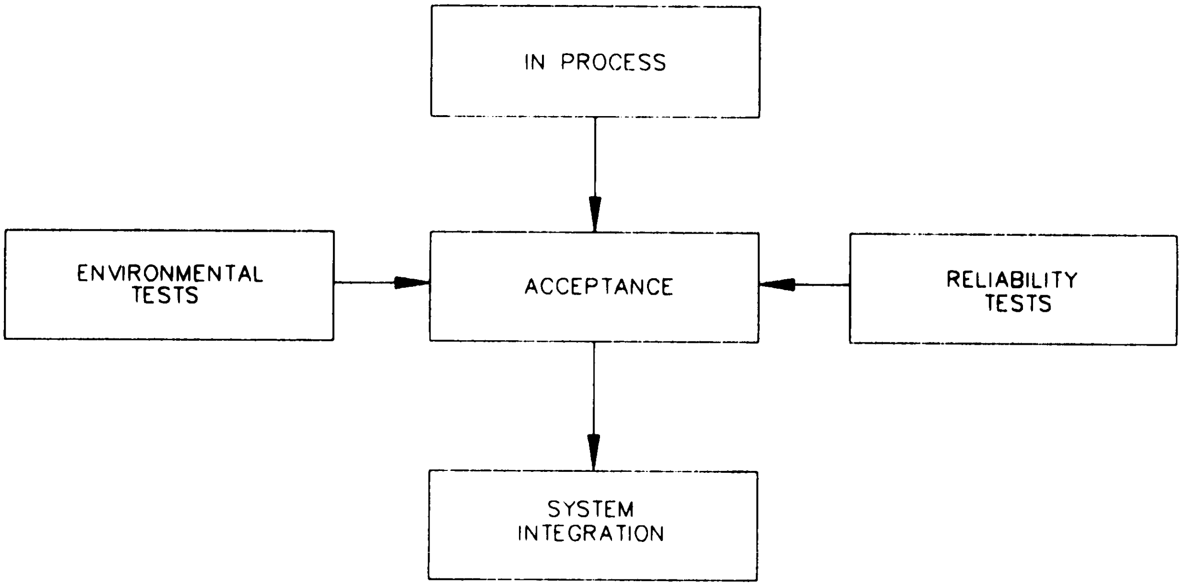


FIGURE 87. Test stages.

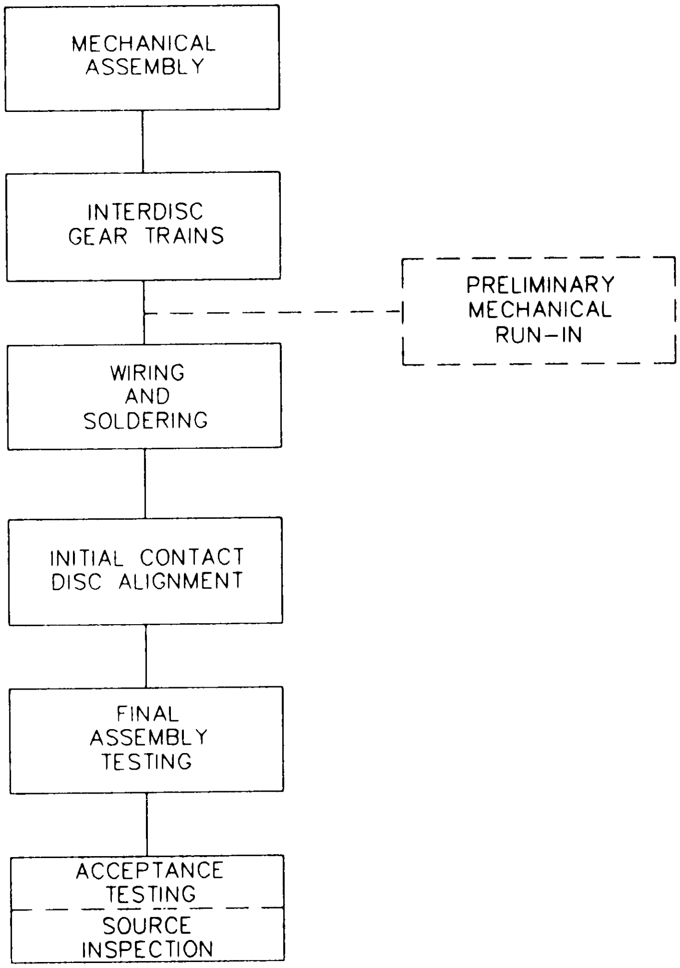


FIGURE 88. Quality assurance requirements.

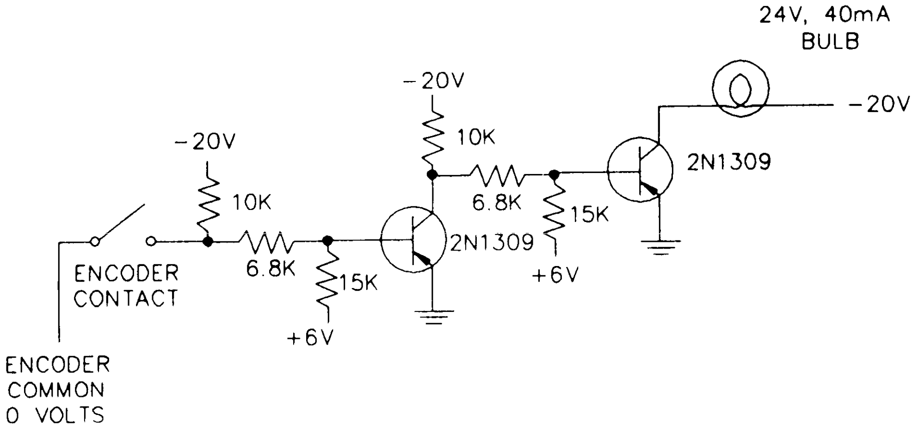


FIGURE 89. Light bank display test circuit.

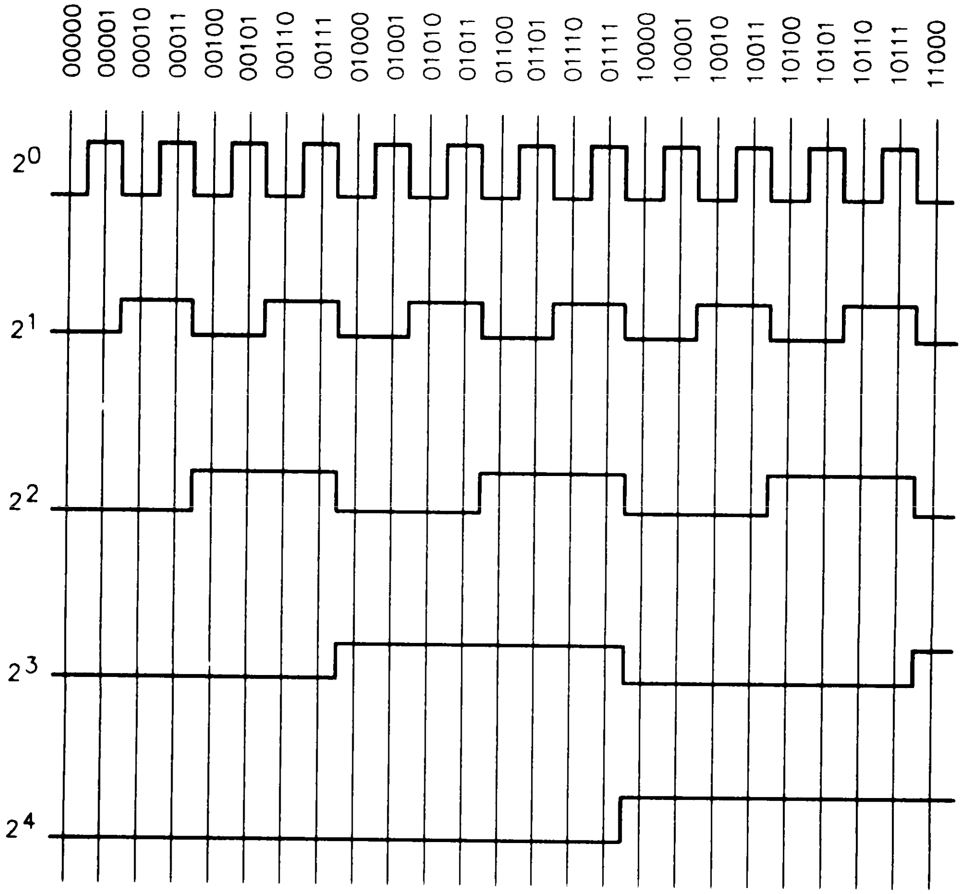


FIGURE 90. Typical oscillograph test traces for natural binary code.

FIGURE 91. Typical buffer circuit.

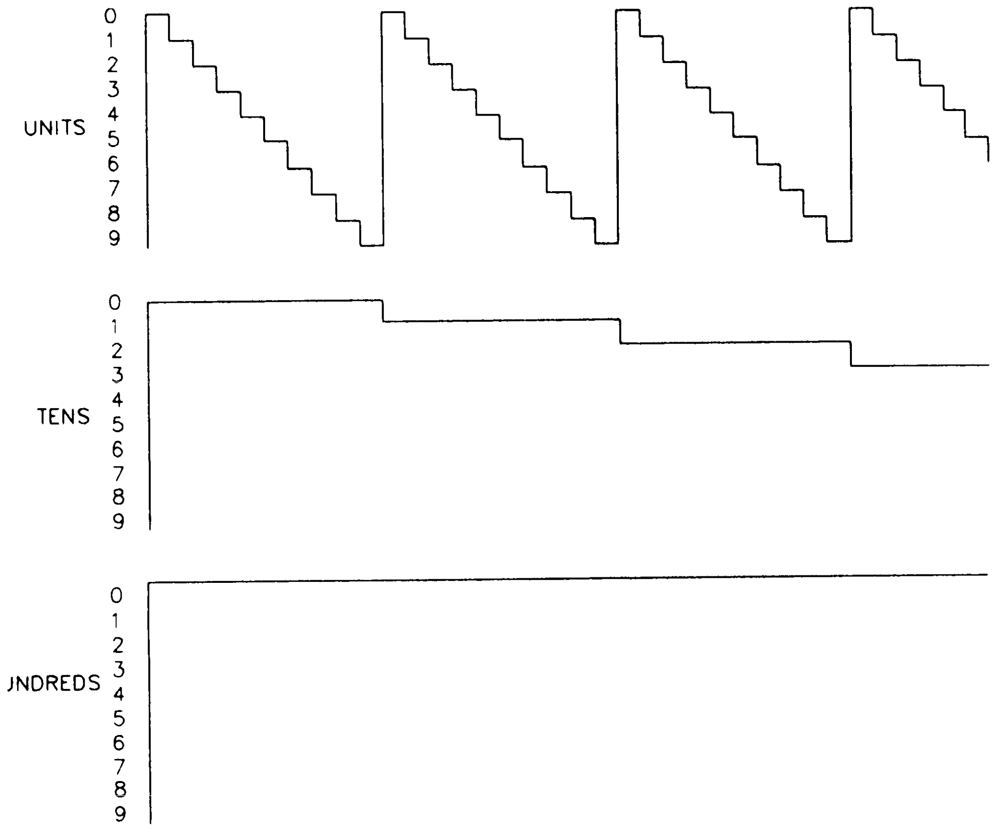


FIGURE 92. Typical oscillograph staircase trace for decimal notation.

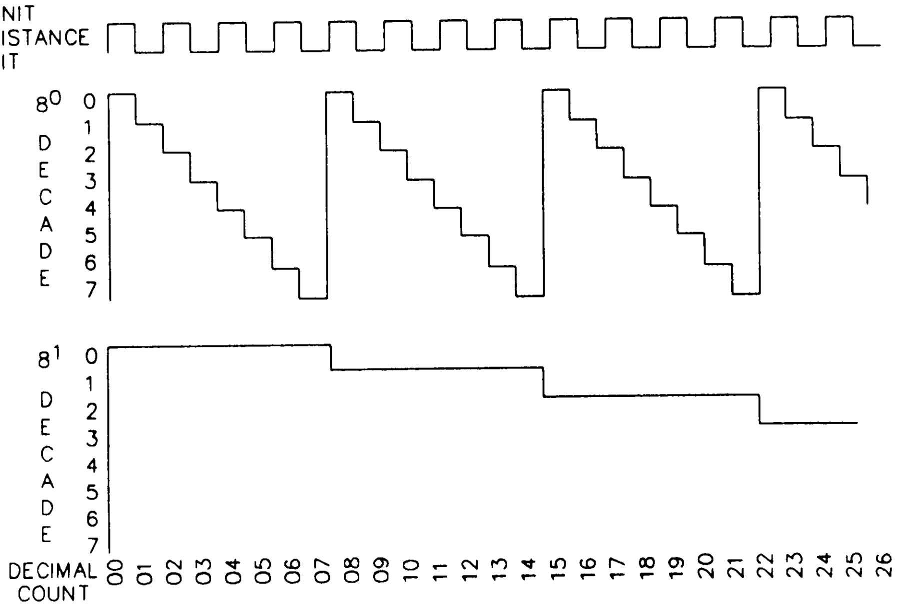
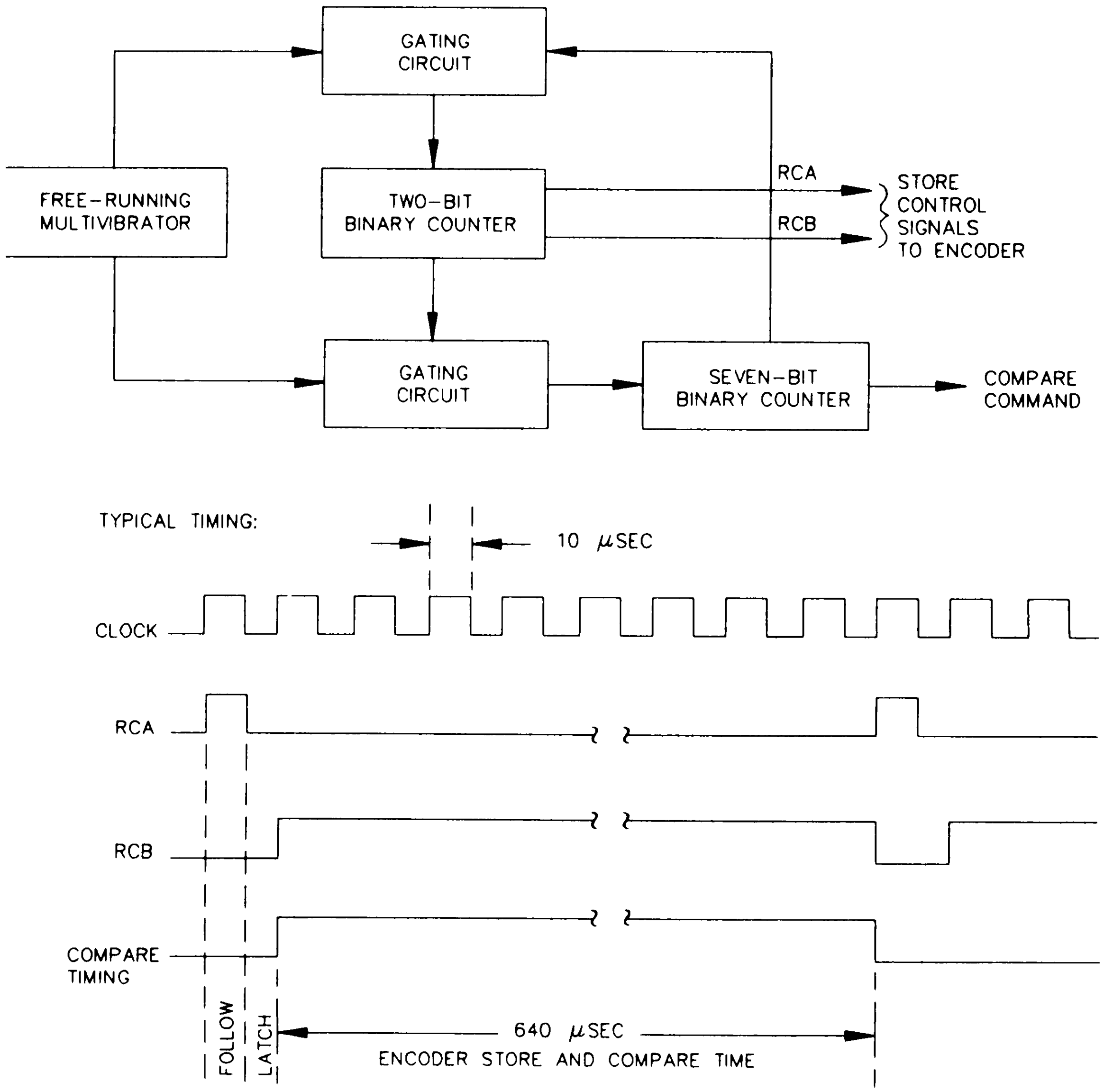


FIGURE 93. Typical oscillograph trace containing unit distance bit and staircase trace for octal notation.



LEGEND:

RCA = READ COMMAND A

RCB = READ COMMAND B

$RCA \cdot \overline{RCB}$ = FOLLOW (READ NEW ENCODER OUTPUT COUNT DATA INTO AUTOCORRELATOR STORAGE REGISTER)

$\overline{RCA} \cdot \overline{RCB}$ = LATCH (CIRCUIT STORES ANY INPUT WHICH IS MOMENTARILY TRUE DURING THIS PERIOD)

$\overline{RCA} \cdot RCB$ = STORE (ENCODER OUTPUT DATA IS HELD CONSTANT AND NOT PERMITTED TO CHANGE)

FIGURE 94. Typical timing Circuit requirements.

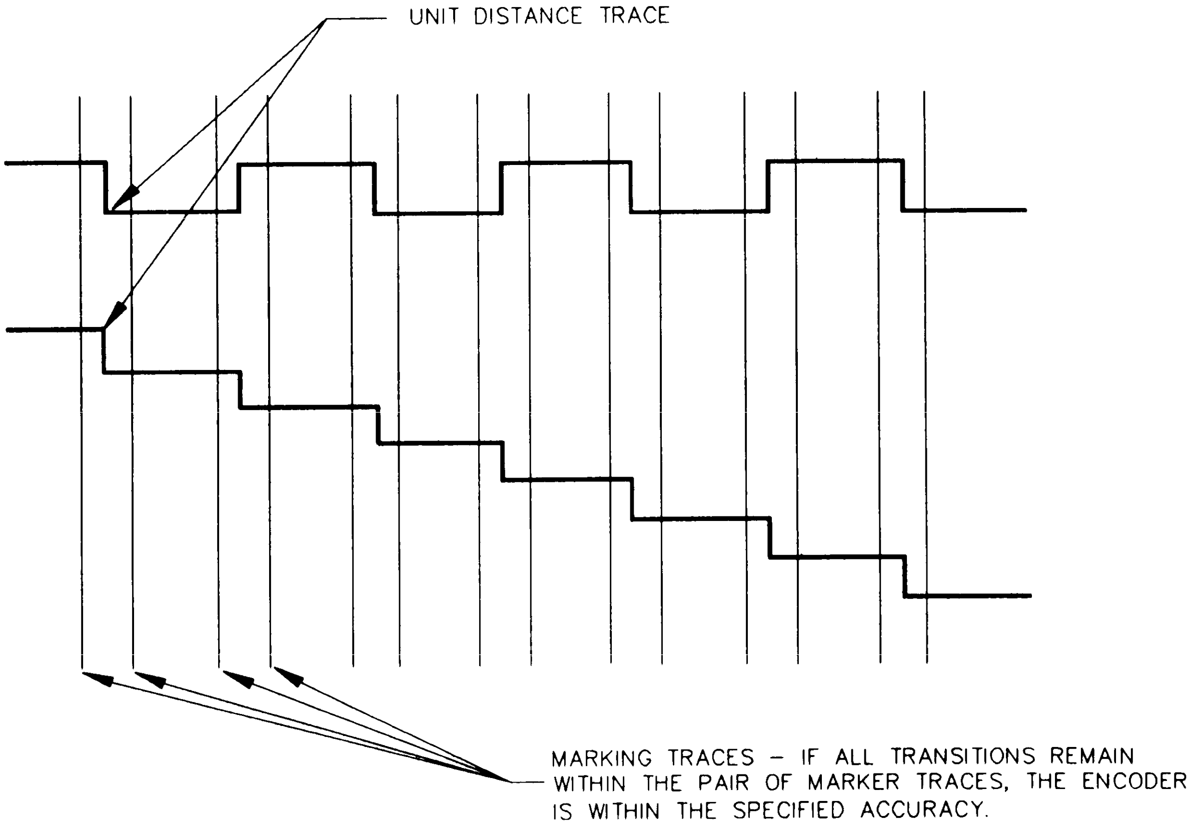
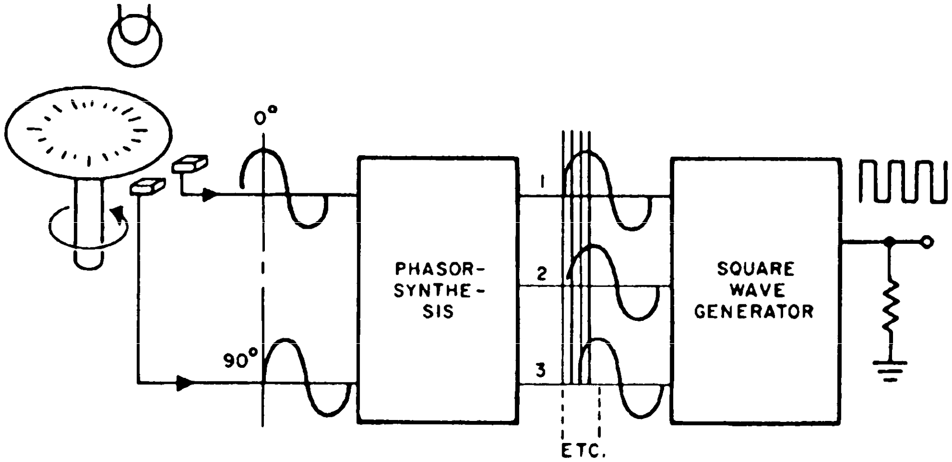
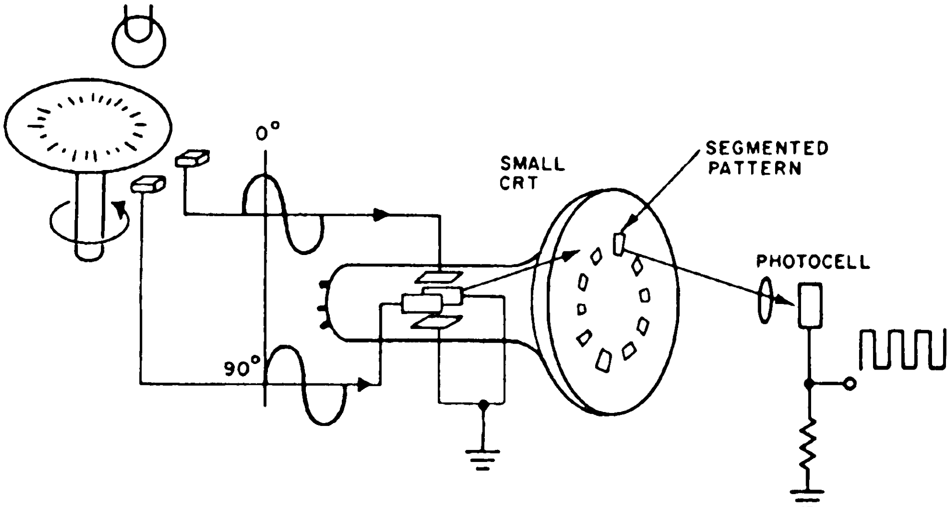


FIGURE 95. Typical oscillograph trace for checking transition accuracy.



PHASESCAN



BEAMSCAN

FIGURE 96. Phasescan and beamscan techniques.

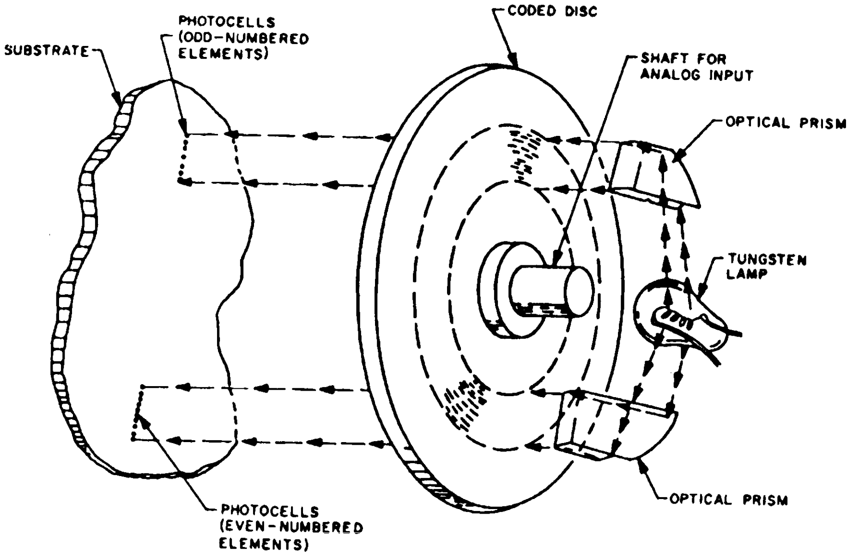


FIGURE 97. Optical encoding scan technique.

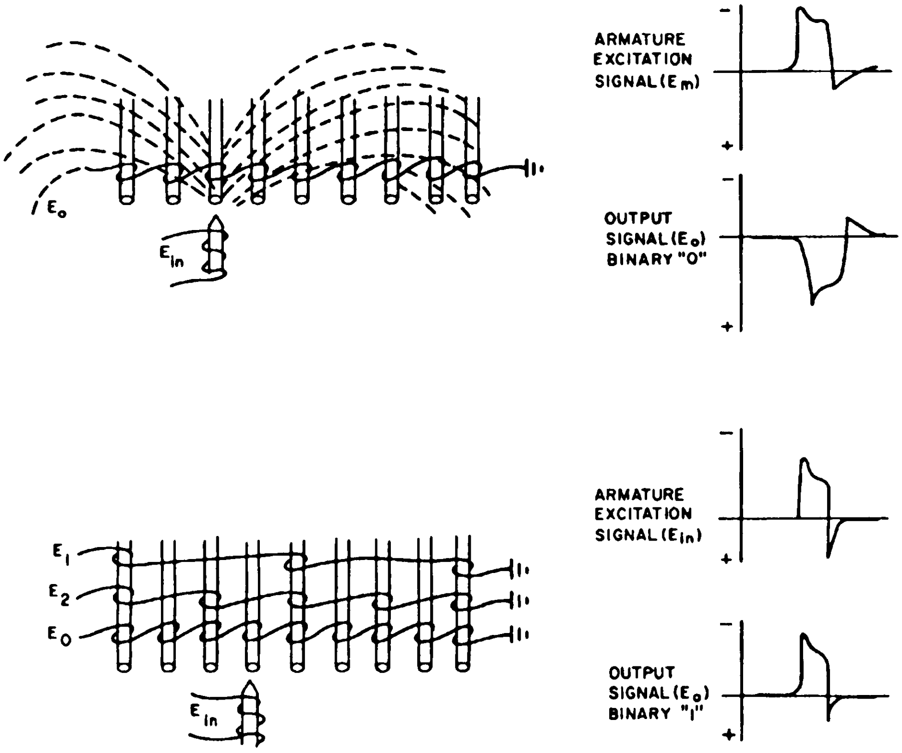


FIGURE 98. Basic approach to a magnetic reluctance digital transducer.

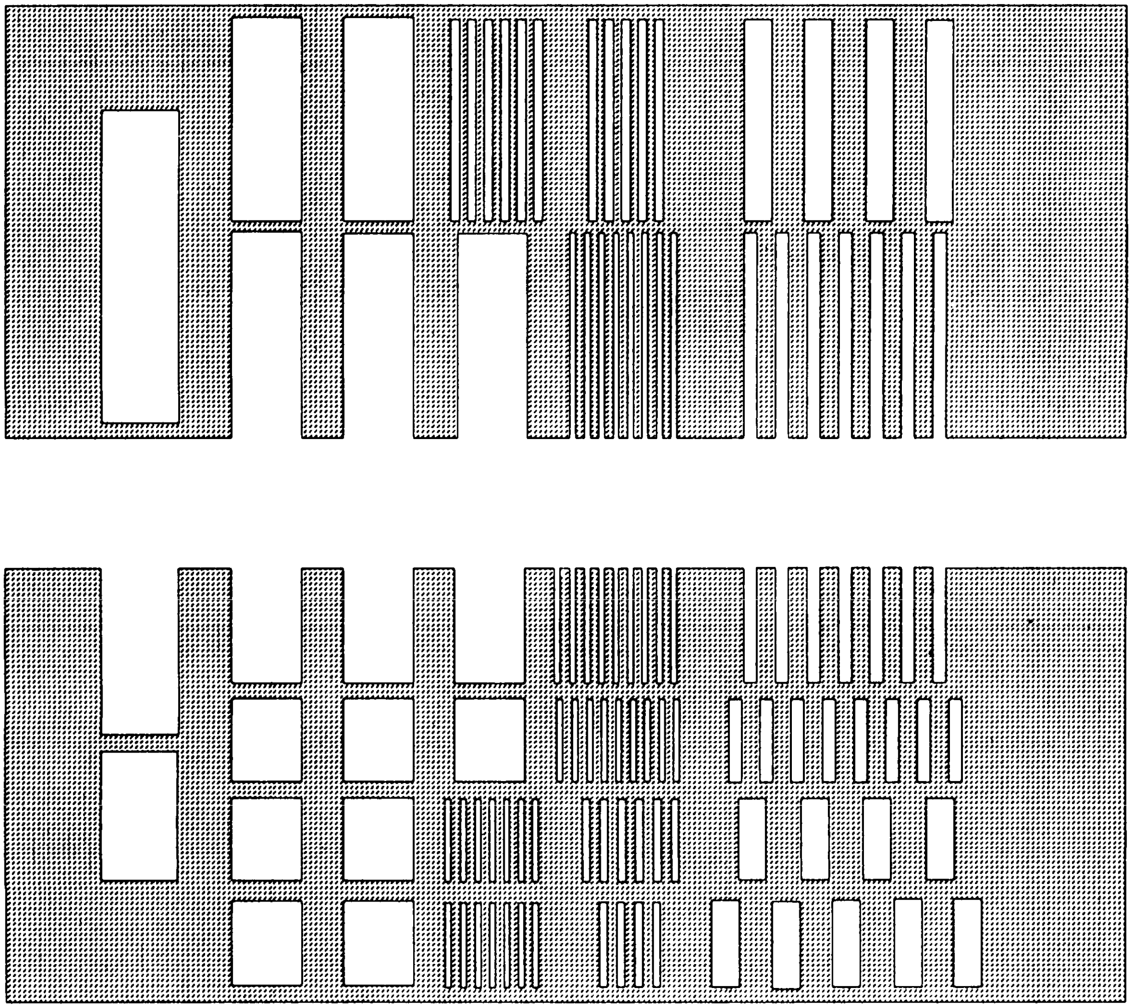


FIGURE 99. Optical rulings for an 11-bit gray code digital transducer.

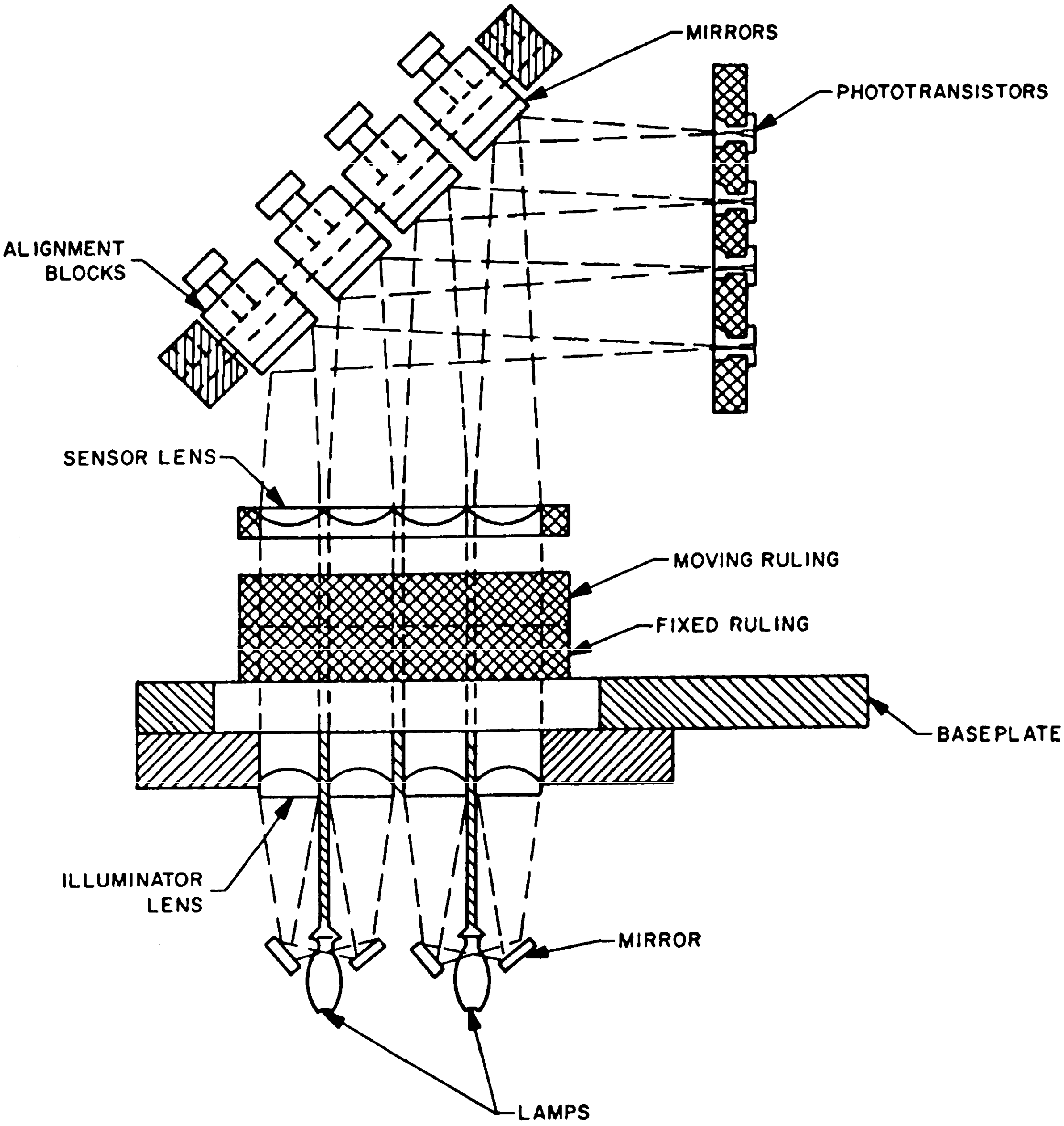


FIGURE 100. Arrangement for an optical digital transducer.

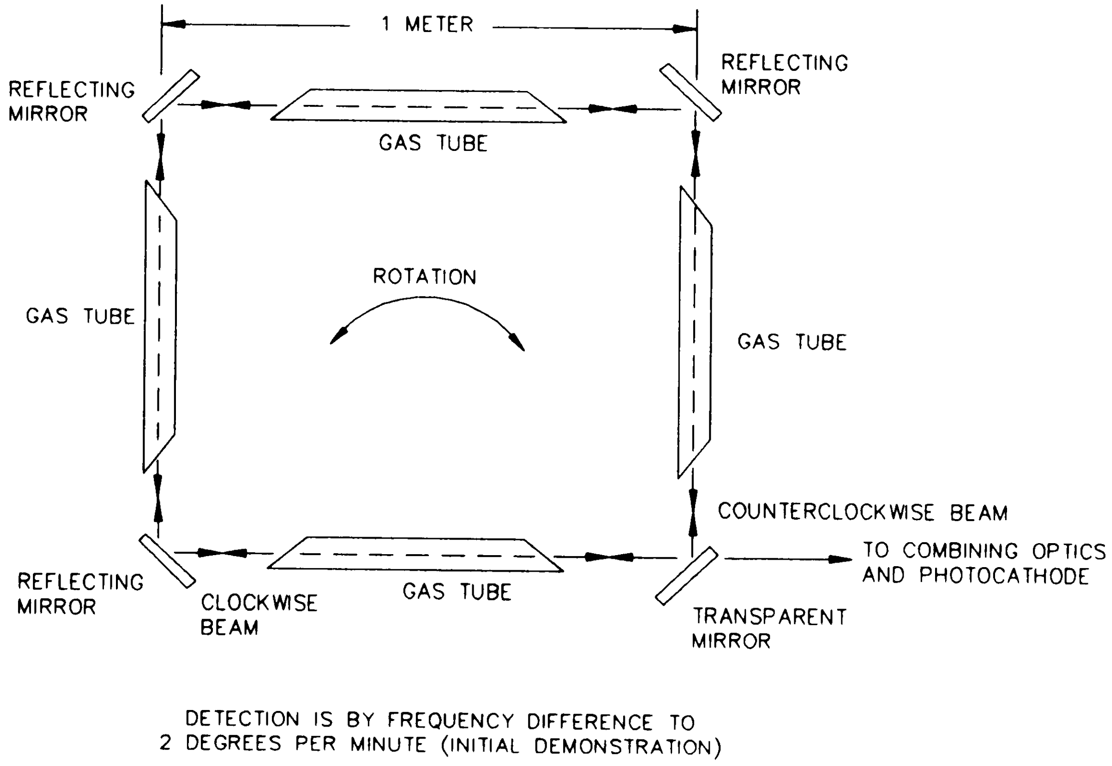


Figure 101. Application of lasers in measurement of rotation.

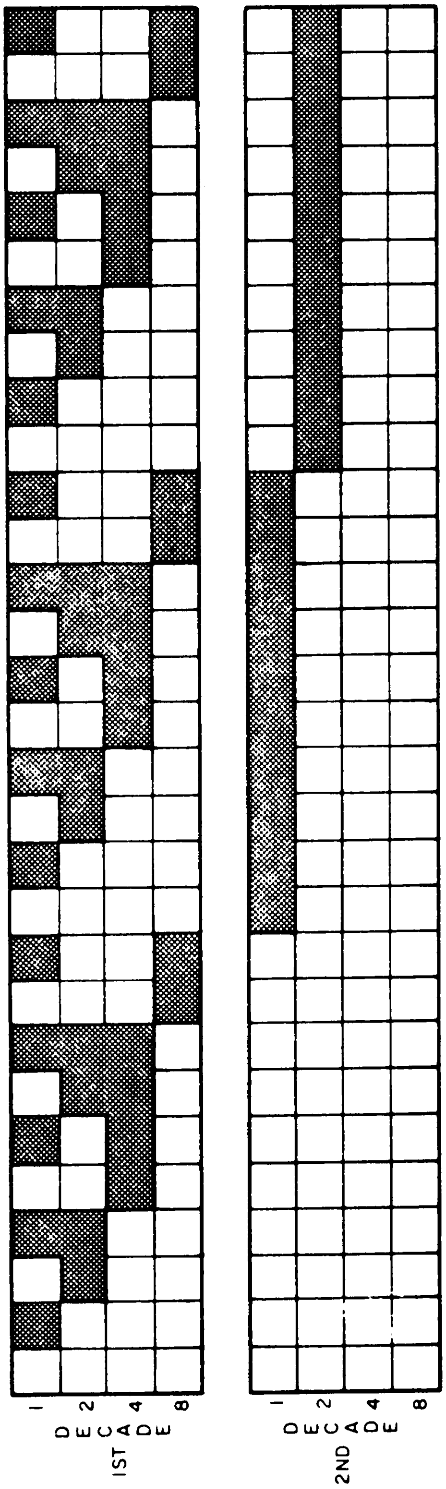


FIGURE 102. Natural binary coded decimal code pattern.

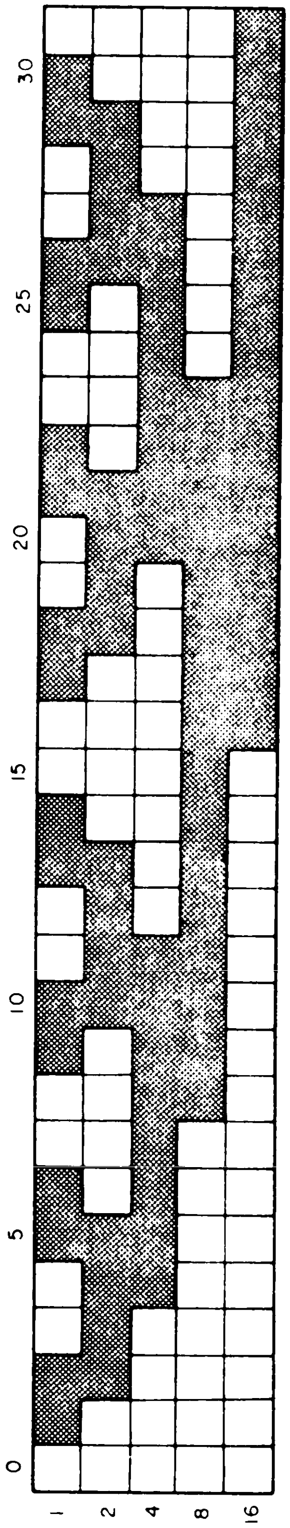
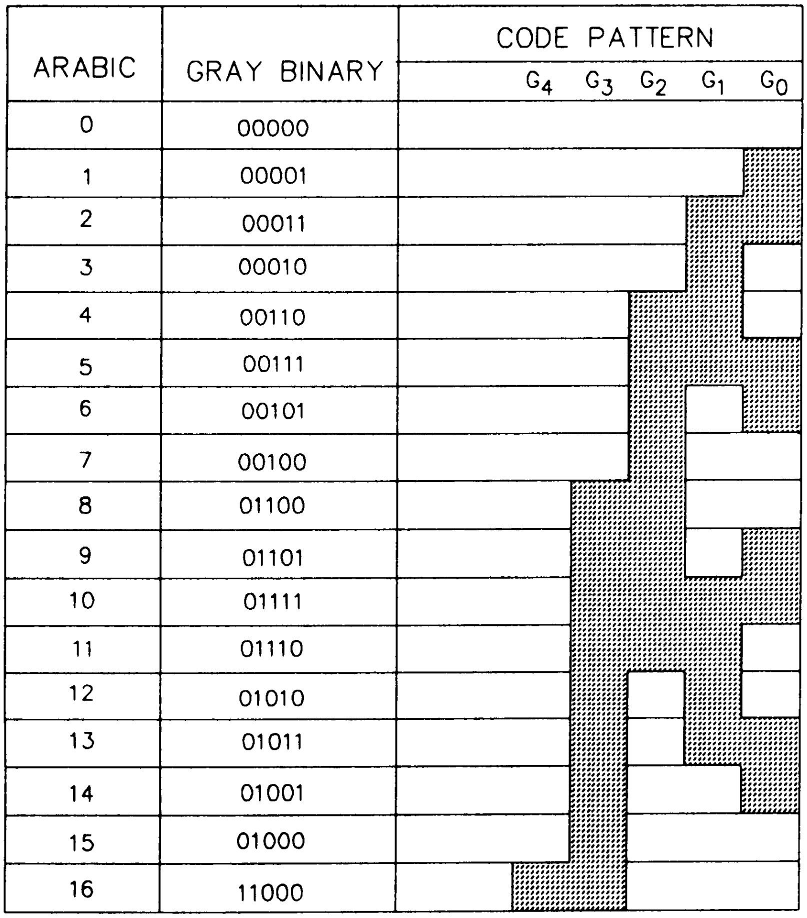


FIGURE 103. Typical 5-bit gray code pattern.



ARABIC	GRAY BINARY	CODE PATTERN				
		G_4	G_3	G_2	G_1	G_0
0	00000					
1	00001					▨
2	00011				▨	▨
3	00010				▨	
4	00110			▨	▨	
5	00111			▨	▨	▨
6	00101			▨		▨
7	00100			▨		
8	01100		▨	▨		
9	01101		▨	▨		▨
10	01111		▨	▨	▨	▨
11	01110		▨	▨	▨	
12	01010		▨		▨	
13	01011		▨		▨	▨
14	01001		▨			▨
15	01000		▨			
16	11000	▨	▨			

FIGURE 104. Gray code progression.

ARABIC DECIMAL	CYCLIC DECIMAL	CYCLIC DECIMAL CODE	
		TENS	UNITS
COUNT	COUNT	ABCD	ABCD
0	0	1000	1000
1	1	1000	1100
2	2	1000	0100
3	3	1000	0110
4	4	1000	0010
5	5	1000	0011
6	6	1000	0111
7	7	1000	0101
8	8	1000	1101
9	9	1000	1001
10	19	1100	1001
11	18	1100	1101
12	17	1100	0101
13	16	1100	0111
14	15	1100	0011
15	14	1100	0010
16	13	1100	0110
17	12	1100	0100
18	11	1100	1100
19	10	1100	1000

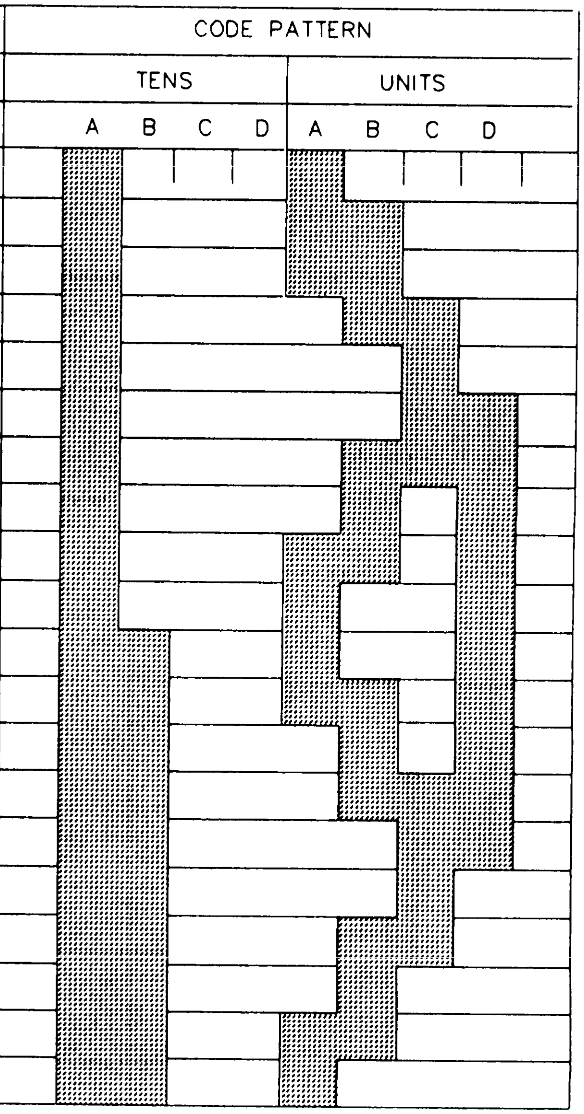


FIGURE 105. Cyclic decimal code progression and pattern.

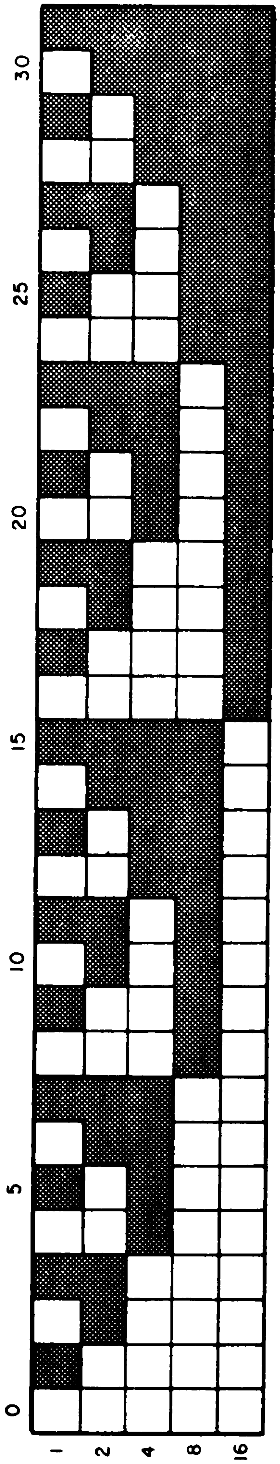


FIGURE 106. Typical 5-bit natural binary pattern.

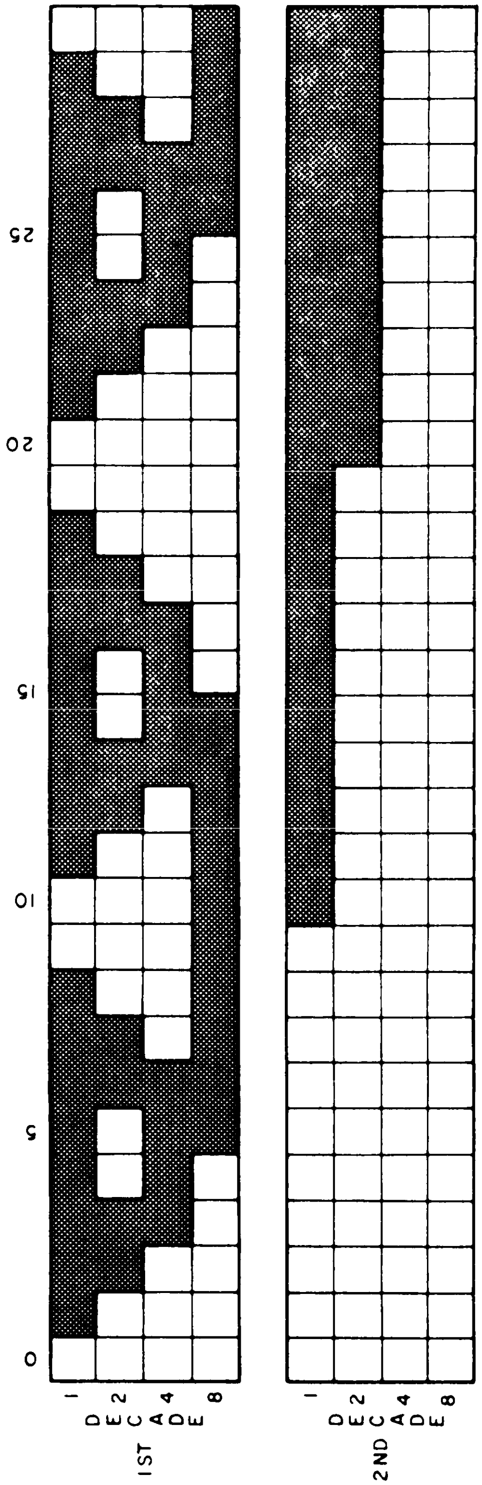


FIGURE 107. Cyclic binary coded decimal code pattern.

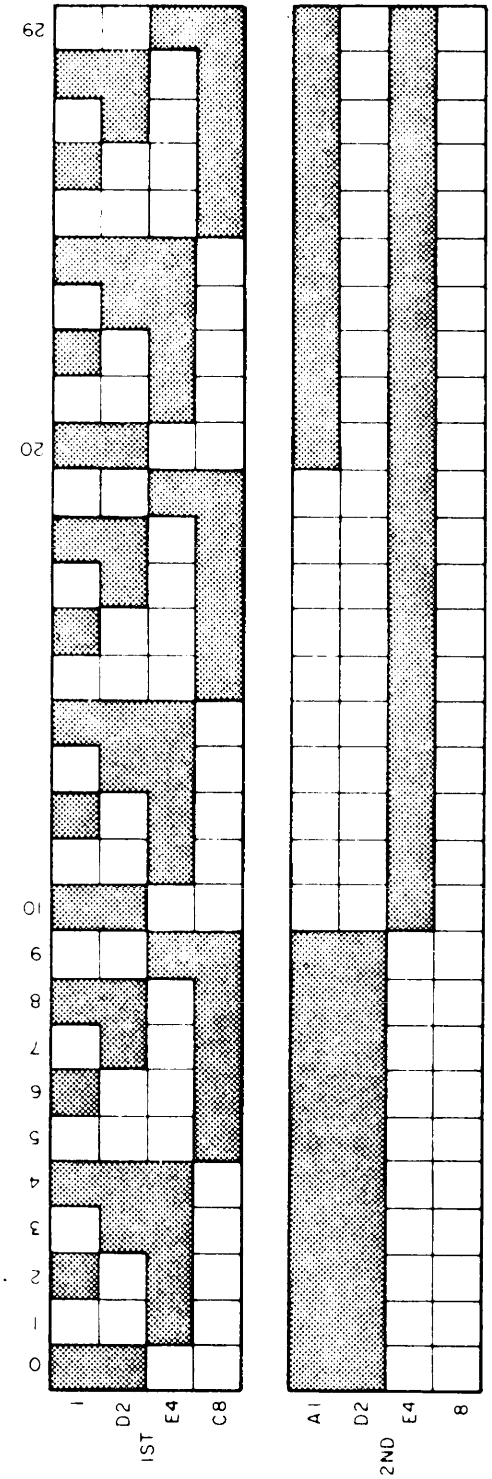


FIGURE 108. Excess three binary coded decimal code pattern.

ALTITUDE (IN FEET)	CYCLIC DECIMAL CODE				GRAY CODE					CODE PATTERN								
	A	B	C	D	G_0	G_1	G_2	G_3	G_4	A	B	C	D	G_0	G_1	G_2	G_3	G_4
1000	0	1	0	0	1	1	0	0	0		▨			▨	▨			
1100	0	1	1	0	1	1	0	0	0		▨	▨		▨	▨			
1200	0	0	1	0	1	1	0	0	0			▨		▨	▨			
1300	0	0	1	1	1	1	0	0	0			▨	▨	▨	▨			
1400	0	1	1	1	1	1	0	0	0		▨		▨	▨	▨			
1500	0	1	0	1	1	1	0	0	0		▨		▨	▨	▨			
1600	1	1	0	1	1	1	0	0	0	▨	▨		▨	▨	▨			
1700	1	0	0	1	1	1	0	0	0	▨			▨	▨	▨			
1800	1	0	0	1	0	1	0	0	0	▨			▨		▨			
1900	1	1	0	1	0	1	0	0	0	▨	▨		▨		▨			
2000	0	1	0	1	0	1	0	0	0		▨		▨		▨			
2100	0	1	1	1	0	1	0	0	0		▨	▨	▨		▨			
2200	0	0	1	1	0	1	0	0	0			▨	▨		▨			

FIGURE 110. ICAO code progression and pattern - gray code combined with 4-bit cyclic decimal.

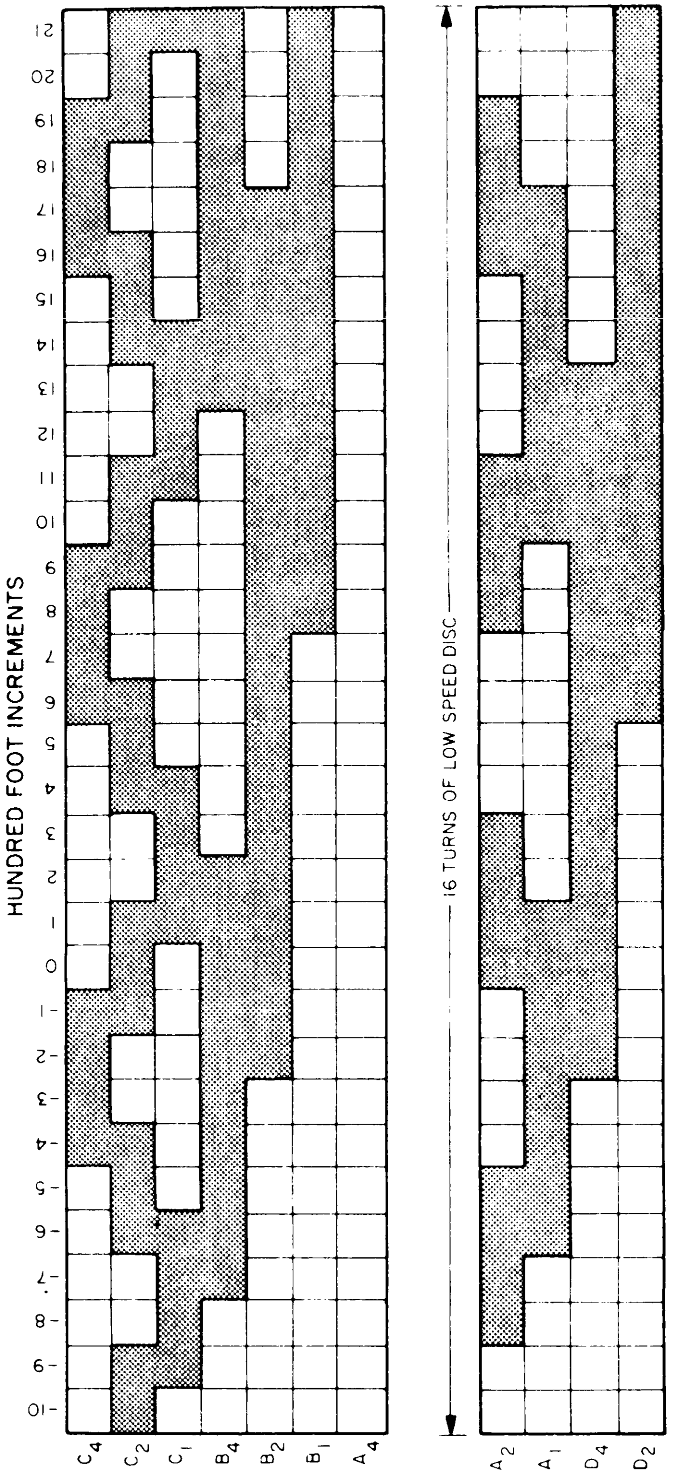


FIGURE 111. ICAO code pattern - gray code combined with 3-bit cyclic decimal.

ARABIC	CODE PATTERN				
	7	4	2	1	P
0	▨	▨			
1				▨	▨
2			▨		▨
3			▨	▨	
4		▨			▨
5		▨		▨	
6		▨	▨		
7	▨				▨
8	▨			▨	
9	▨		▨		

FIGURE 113. Two-out-of-five code.

ARABIC	BIQUINARY CODE		CODE PATTERN							
	86420	ODD		8	6	4	2	0	ODD	
0	00001	0						▨		
1	00001	1						▨	▨	
2	00001	0					▨			
3	00010	1					▨		▨	
4	00100	0				▨				
5	00100	1				▨			▨	
6	01000	0			▨					
7	01000	1			▨				▨	
8	10000	0		▨						
9	10000	1		▨					▨	

FIGURE 114. Odd/even biauinary code progression and pattern.

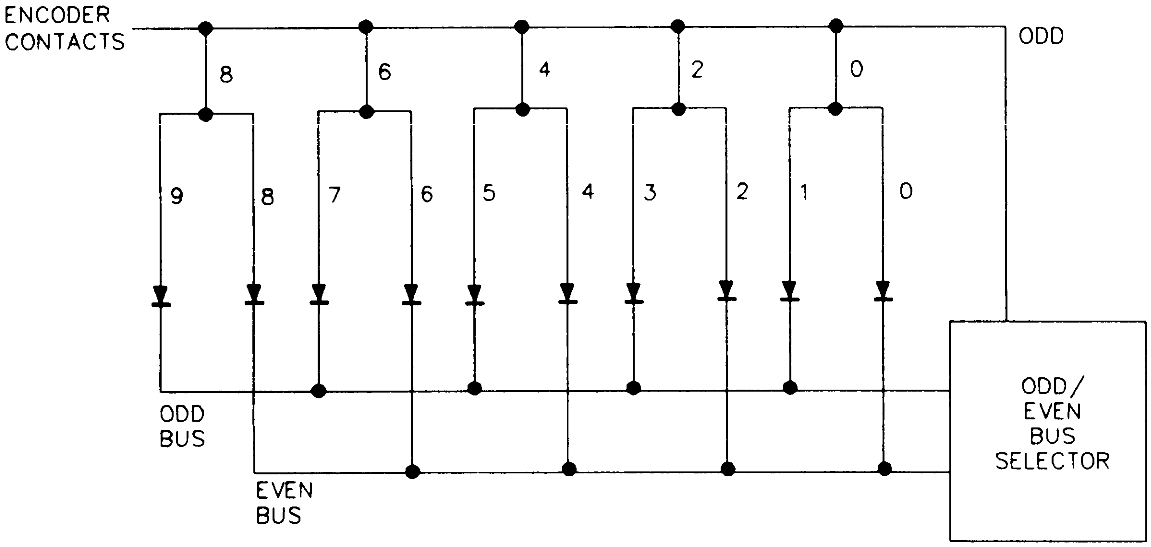


FIGURE 115. Typical odd/even biquinary output circuit.

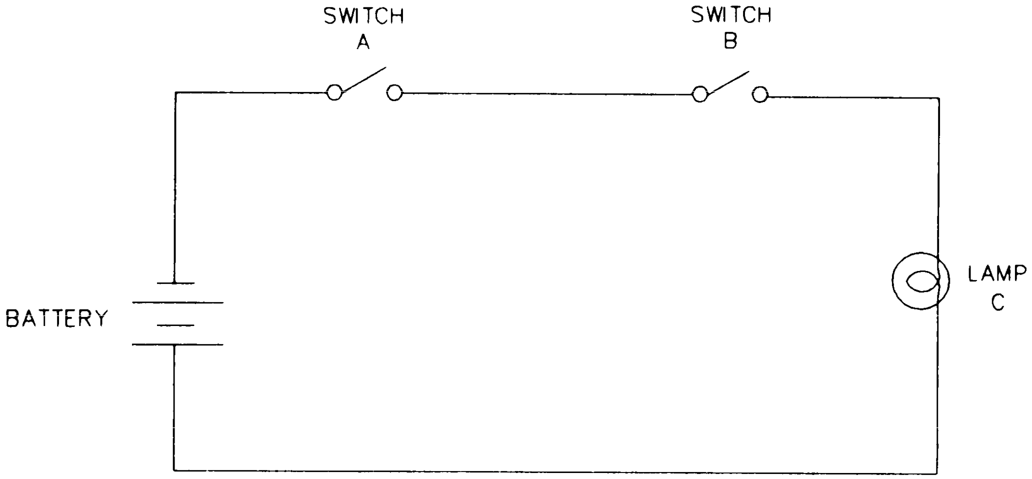


FIGURE 116. Series circuit illustrating AND function.

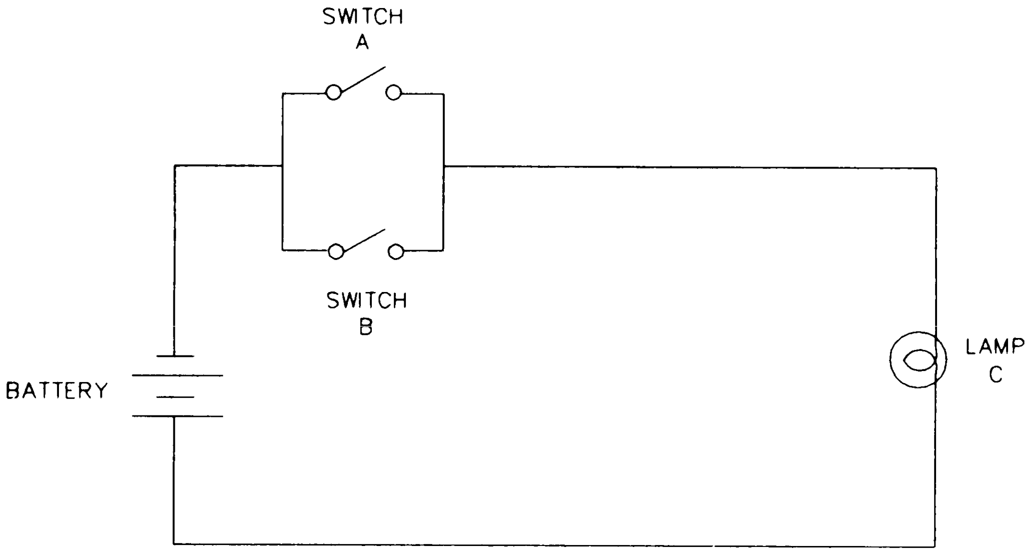


FIGURE 117. Parallel circuit illustrating inclusive OR function.

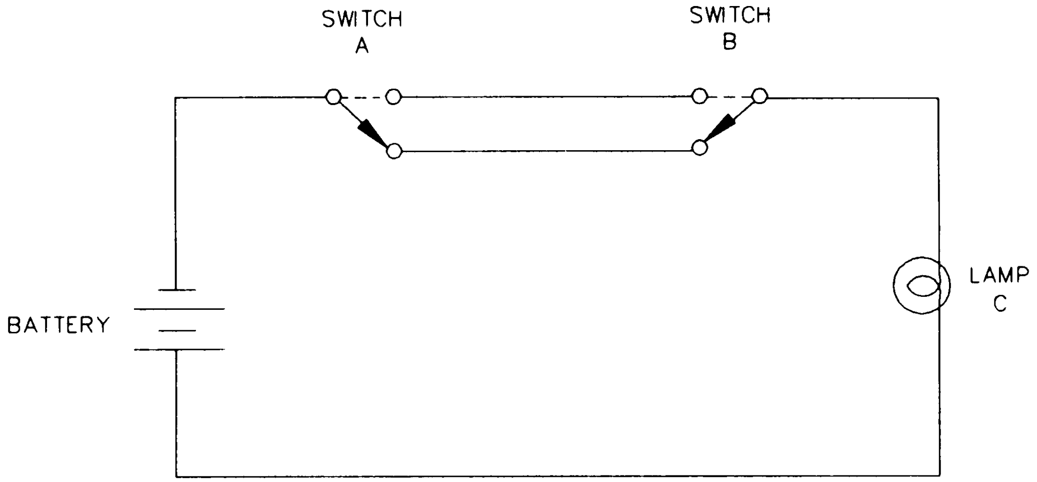


FIGURE 118. Pictorial of exclusive OR function.

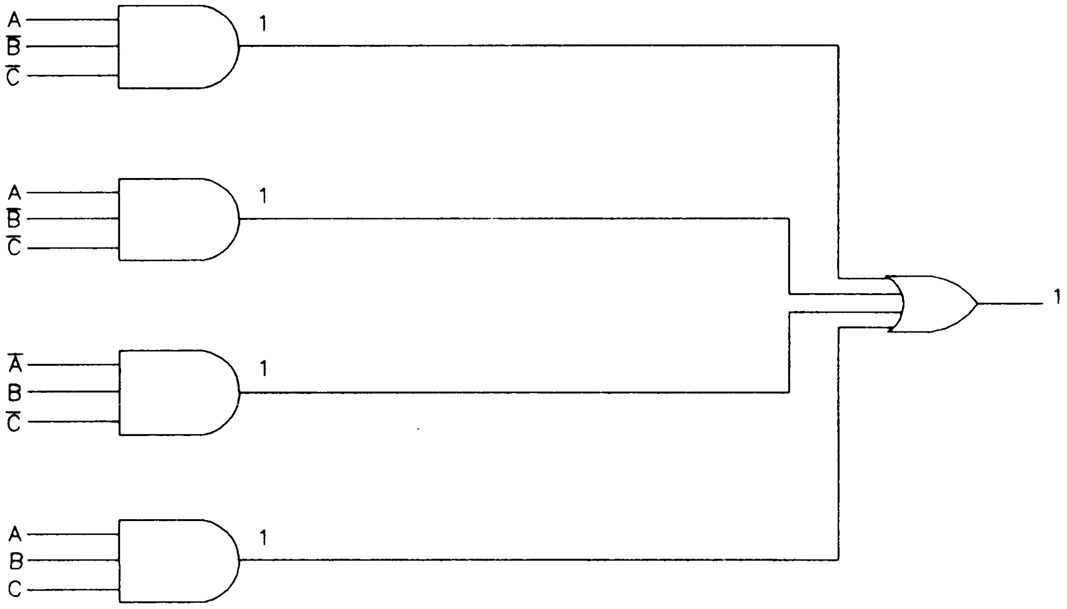


FIGURE 119. Sample logic diagram.

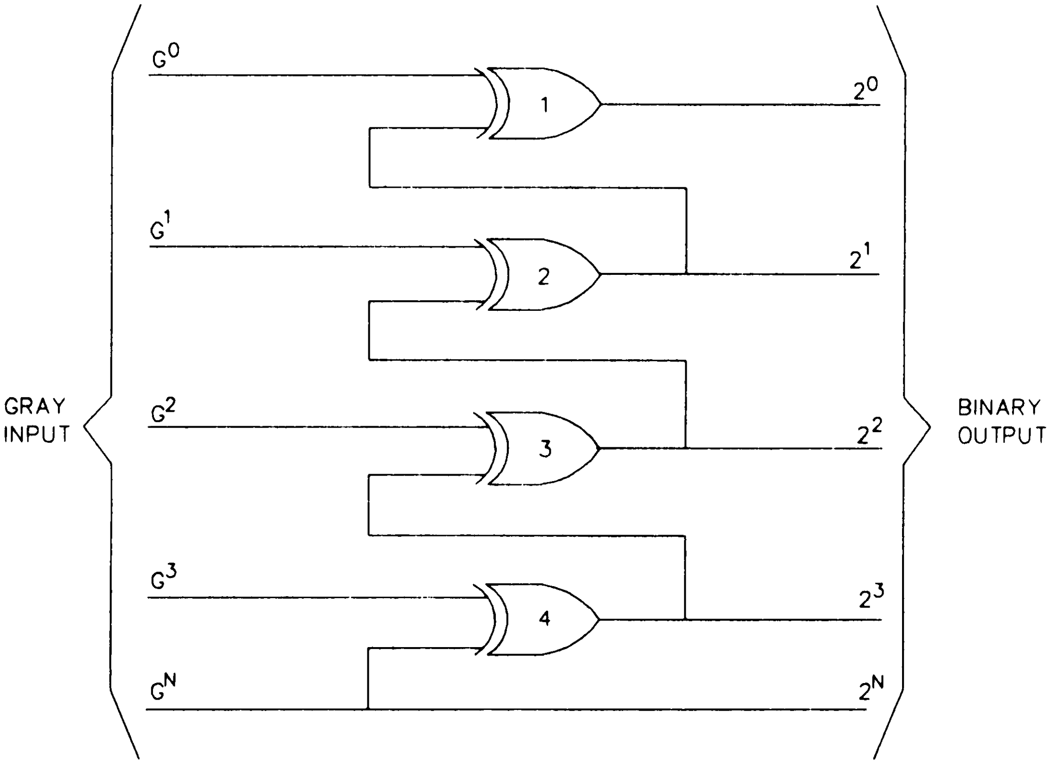


FIGURE 120. Parallel gray code transition to binary.

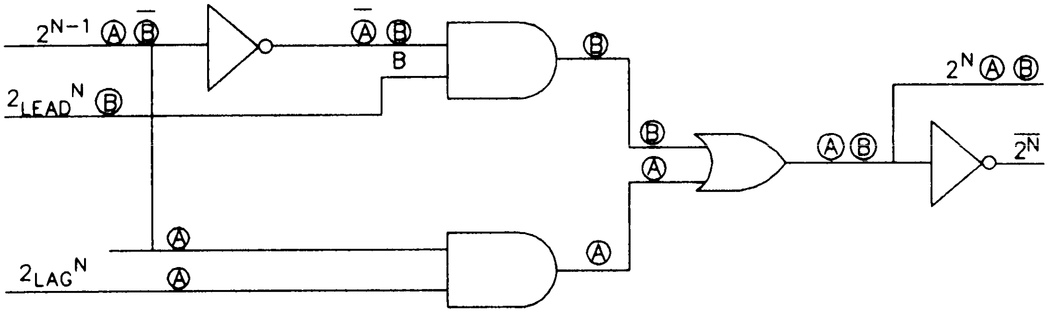


FIGURE 121. Logic diagram for V-scan brush selection.

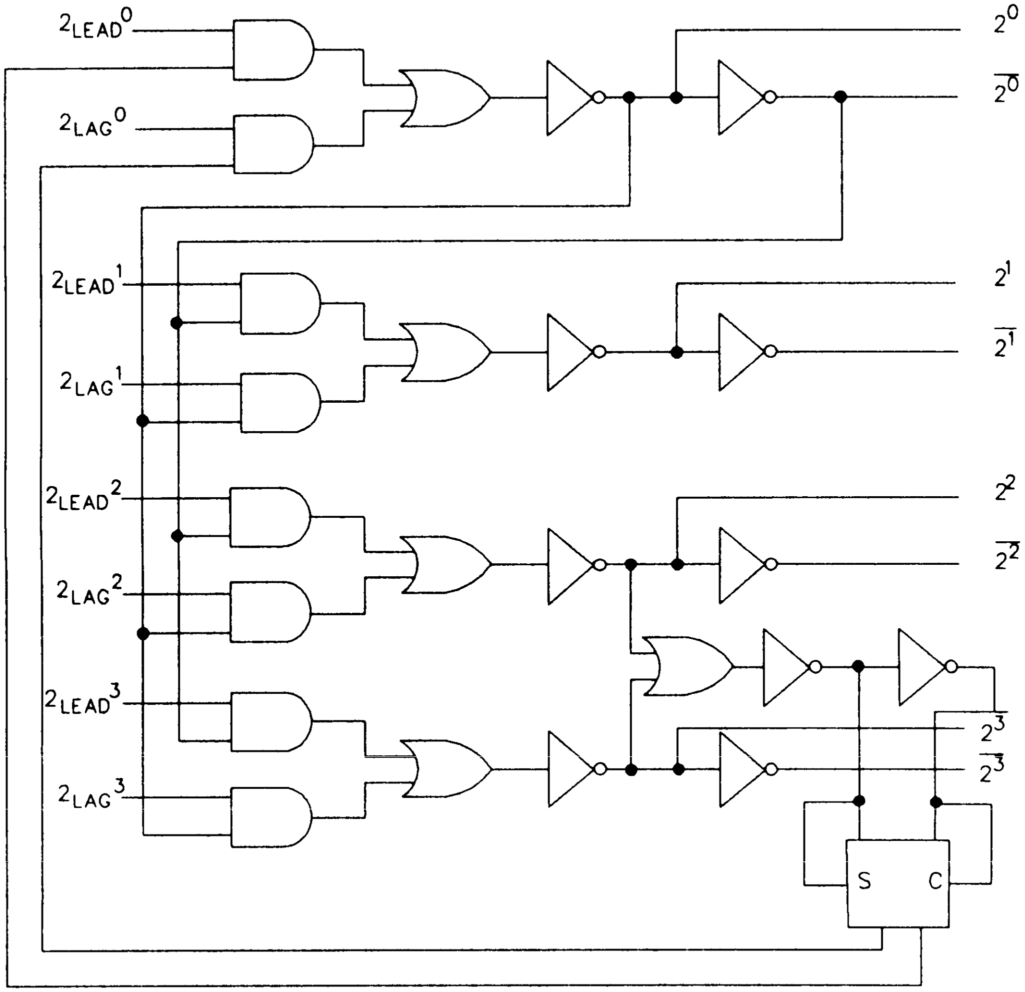


FIGURE 122. Lead-lag sensor selection, BCD processing, serial output.

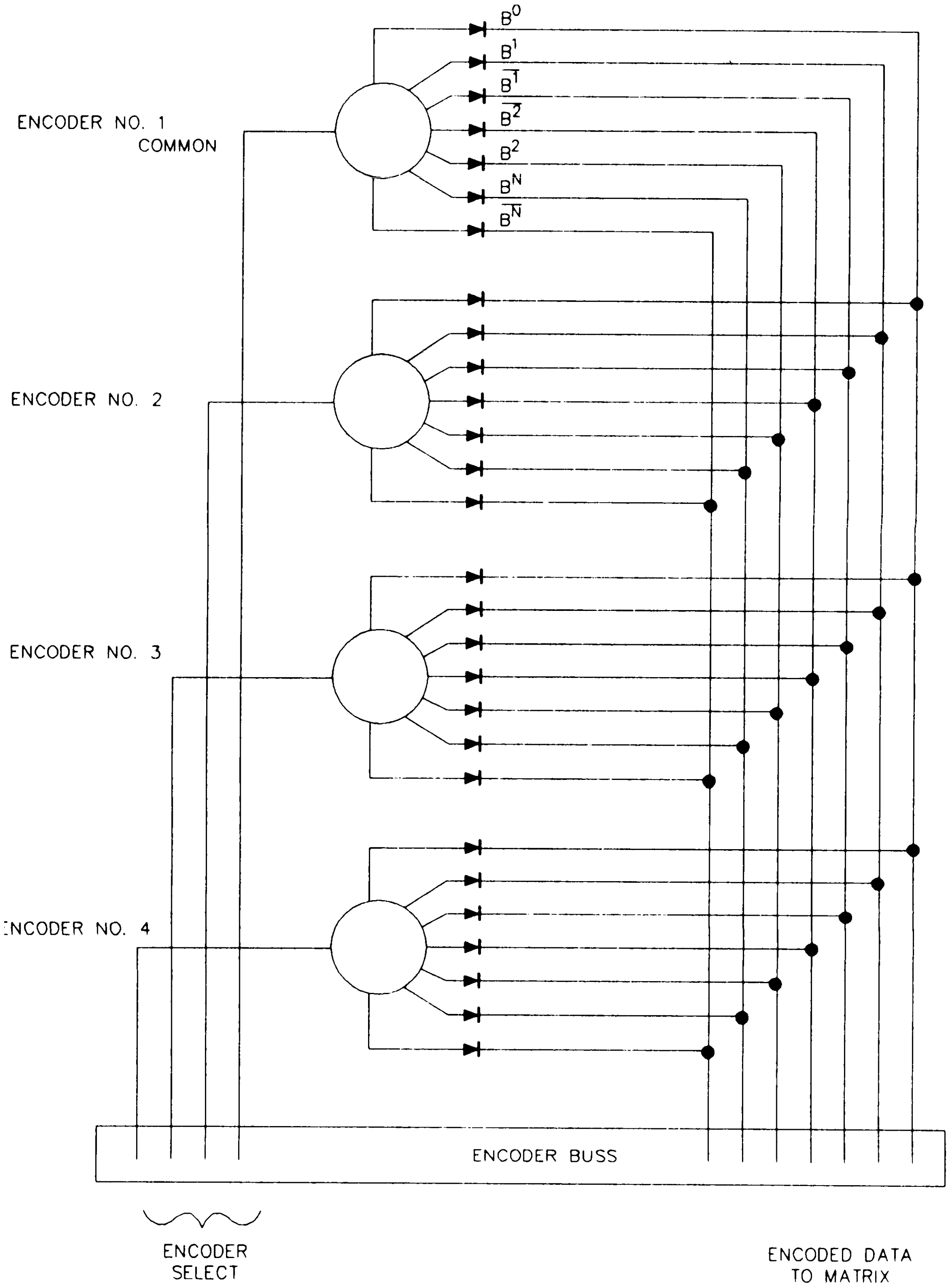


FIGURE 123. Multiple encoder system, time shared output.

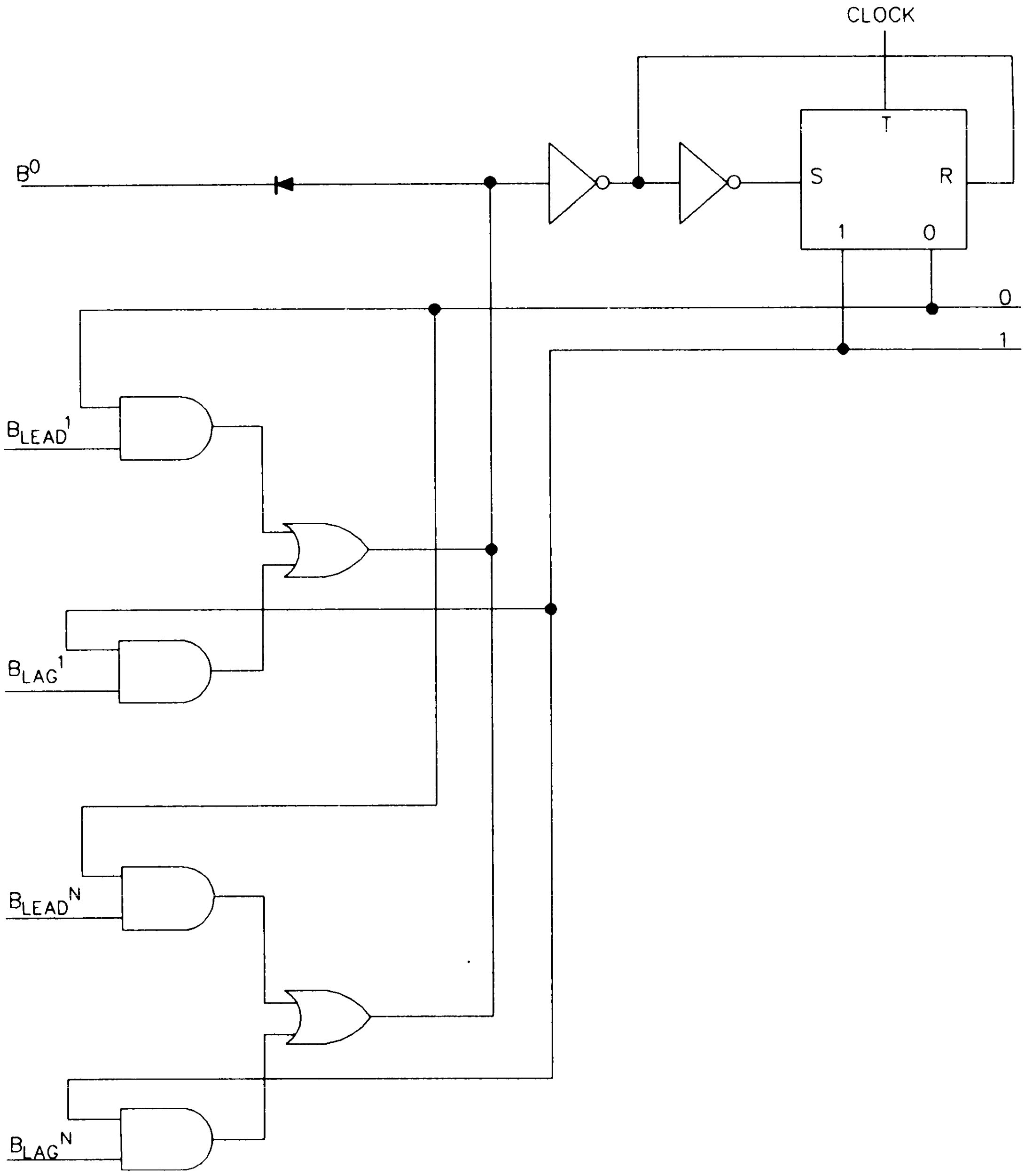


FIGURE 124. Serial scan matrix, logic diagram, V-scan applications.

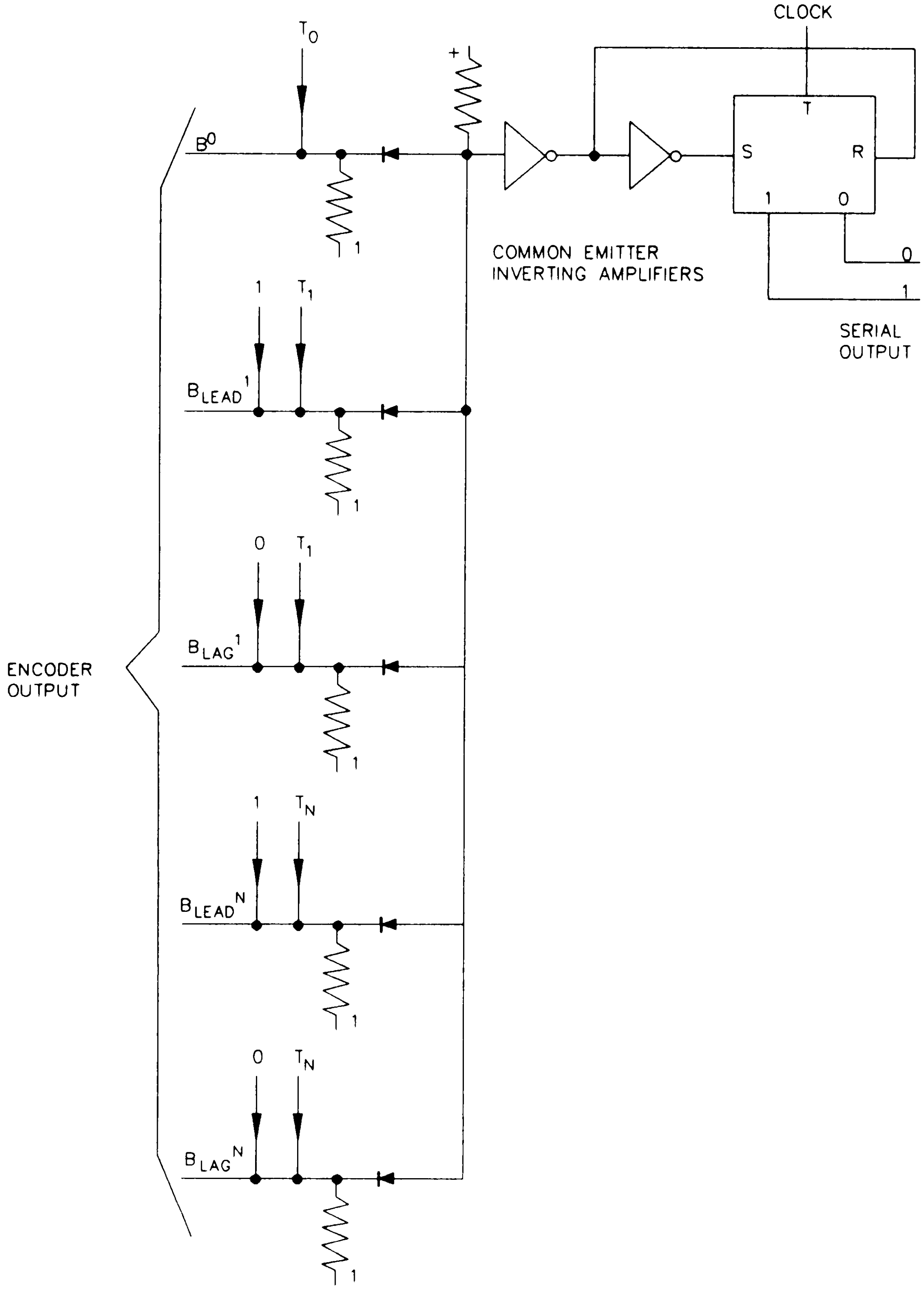


FIGURE 125. Serial scan matrix, simplified schematic diagram, V-scan applications, DTL configuration.

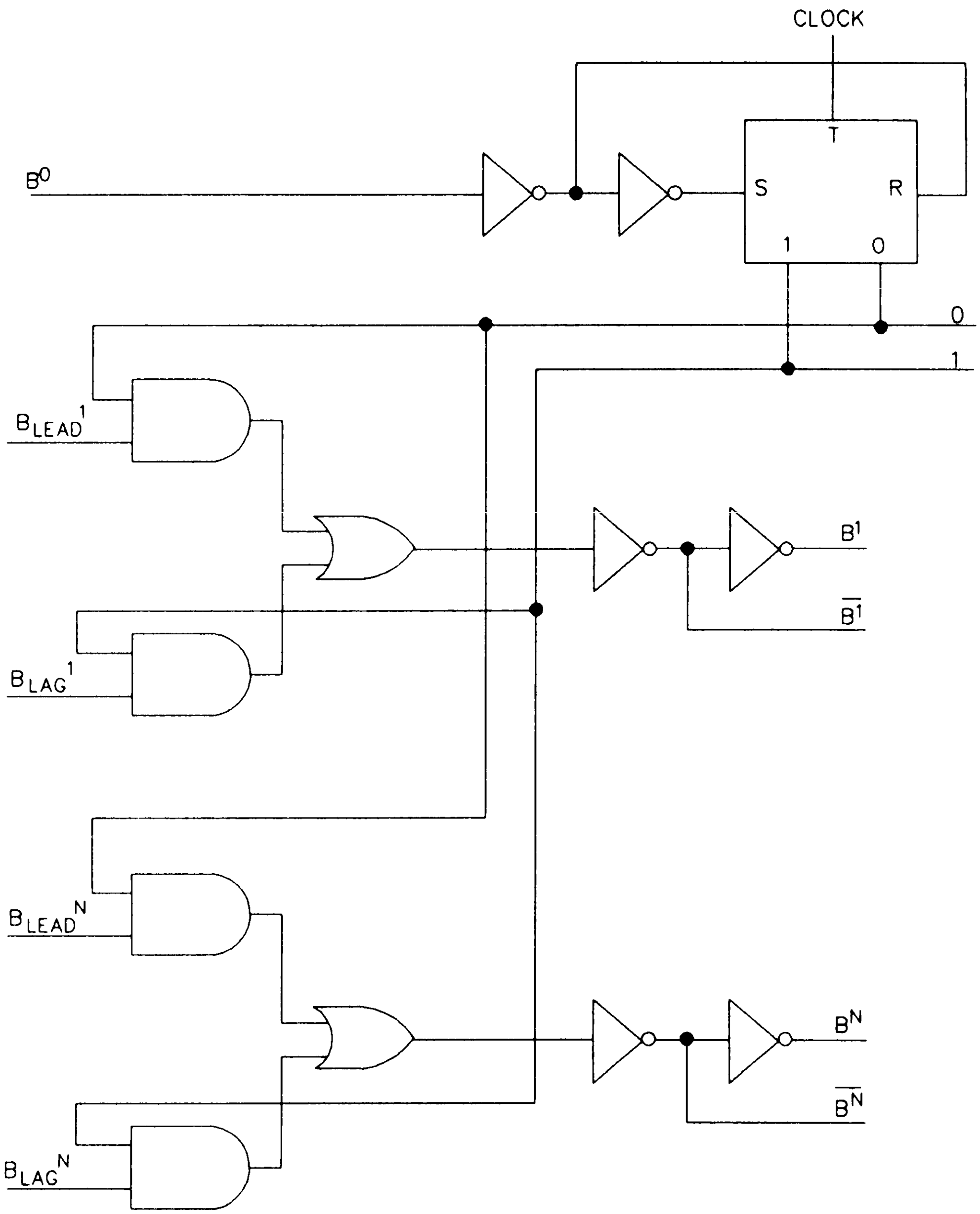


FIGURE 126. Parallel scan matrix, logic diagram, V-scan applications.

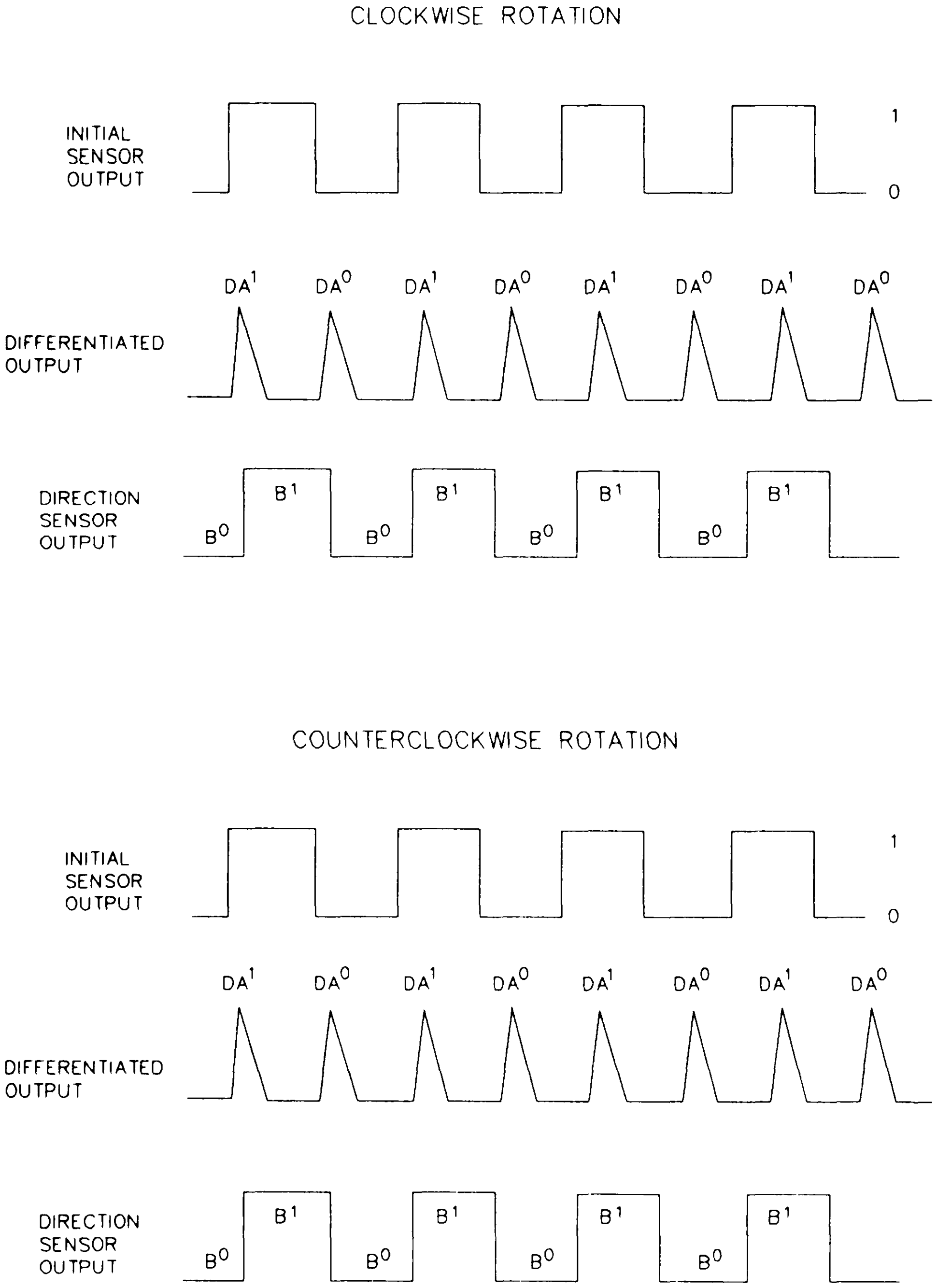


FIGURE 127. Direction sensing, waveforms and timing sequence.

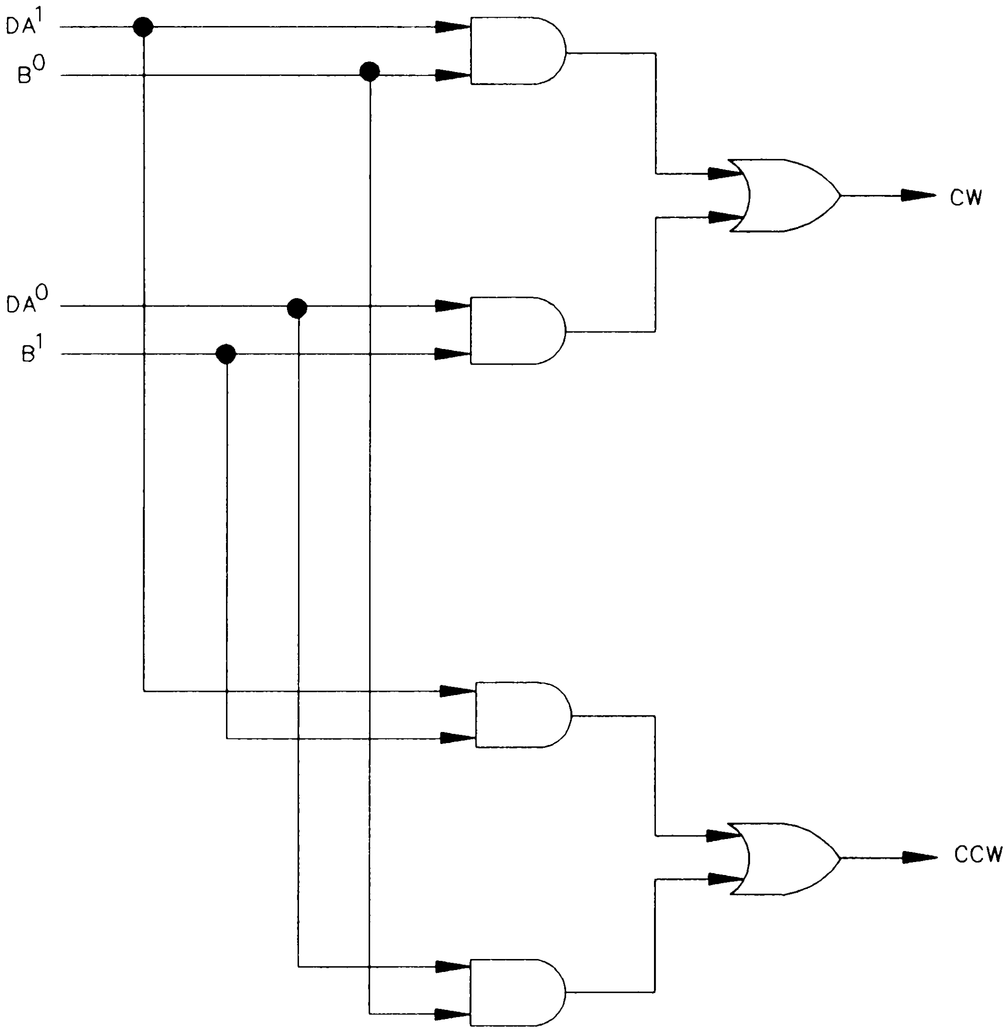


FIGURE 128. Direction sensing, logic diagram.

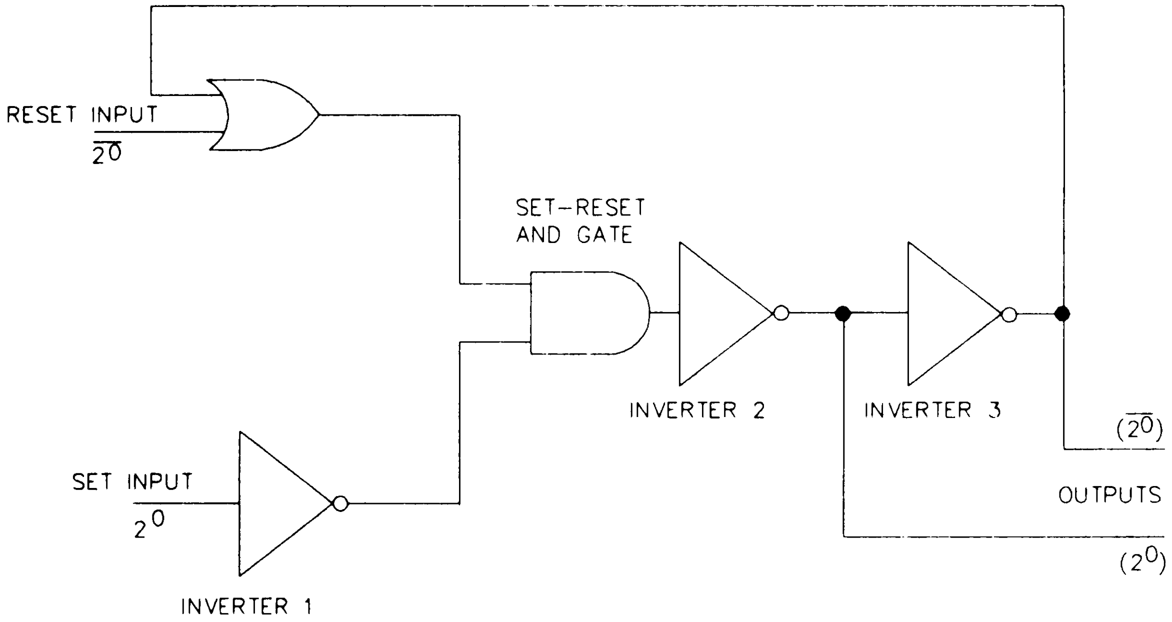


FIGURE 129. Set-reset, logic diagram.

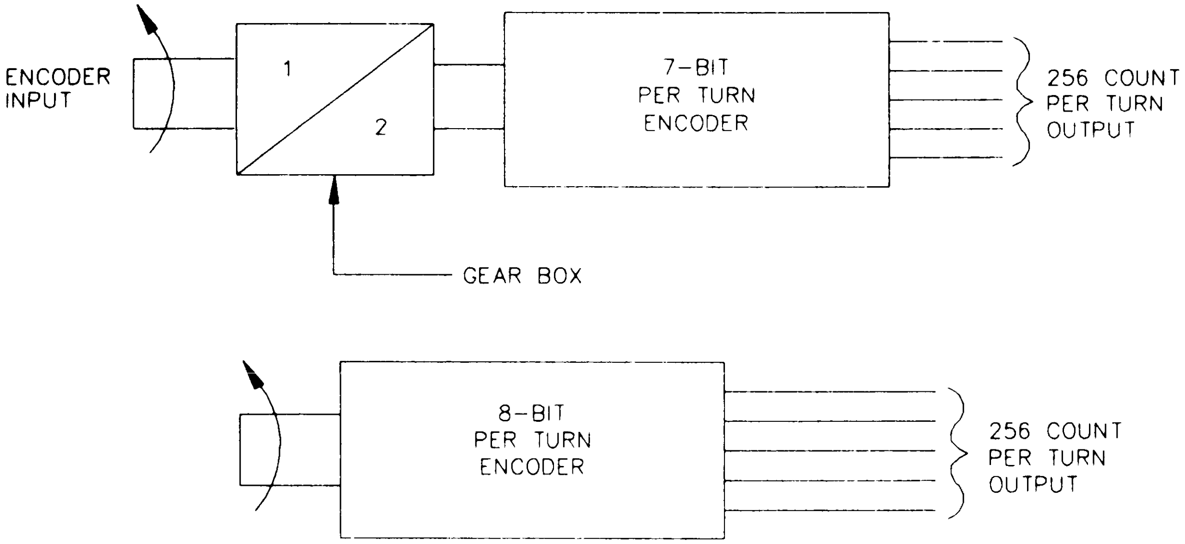


FIGURE 130. Reliability comparison.

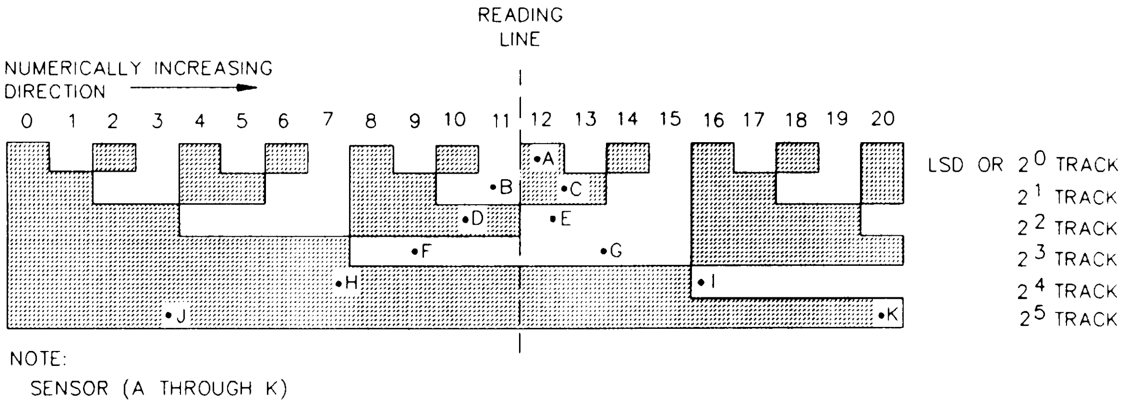


FIGURE 131. V-scan technique using staggered sensors.

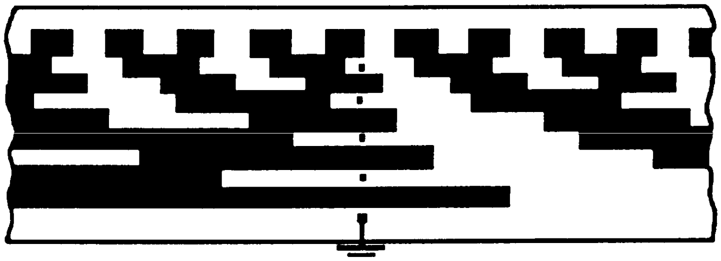


FIGURE 132. V-scan technique using V-disc.

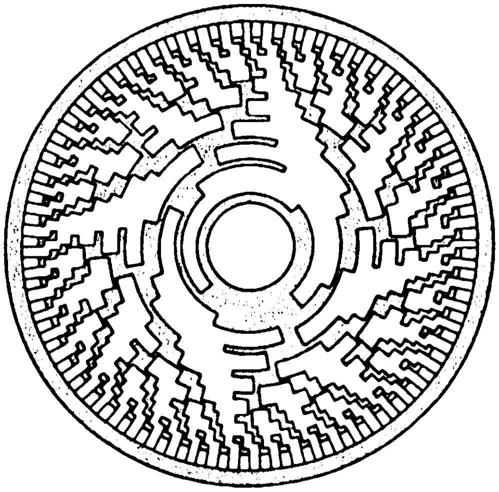


FIGURE 133. V-scan disc.

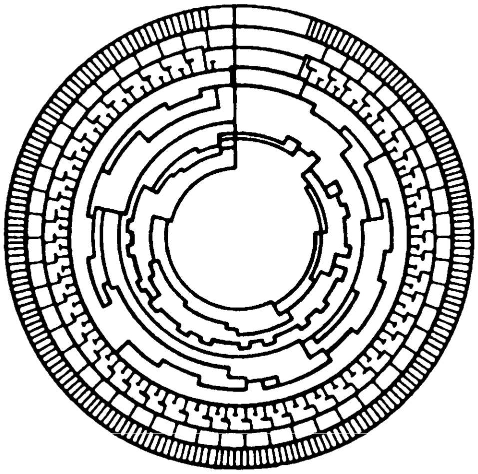


FIGURE 134. U-scan disc.

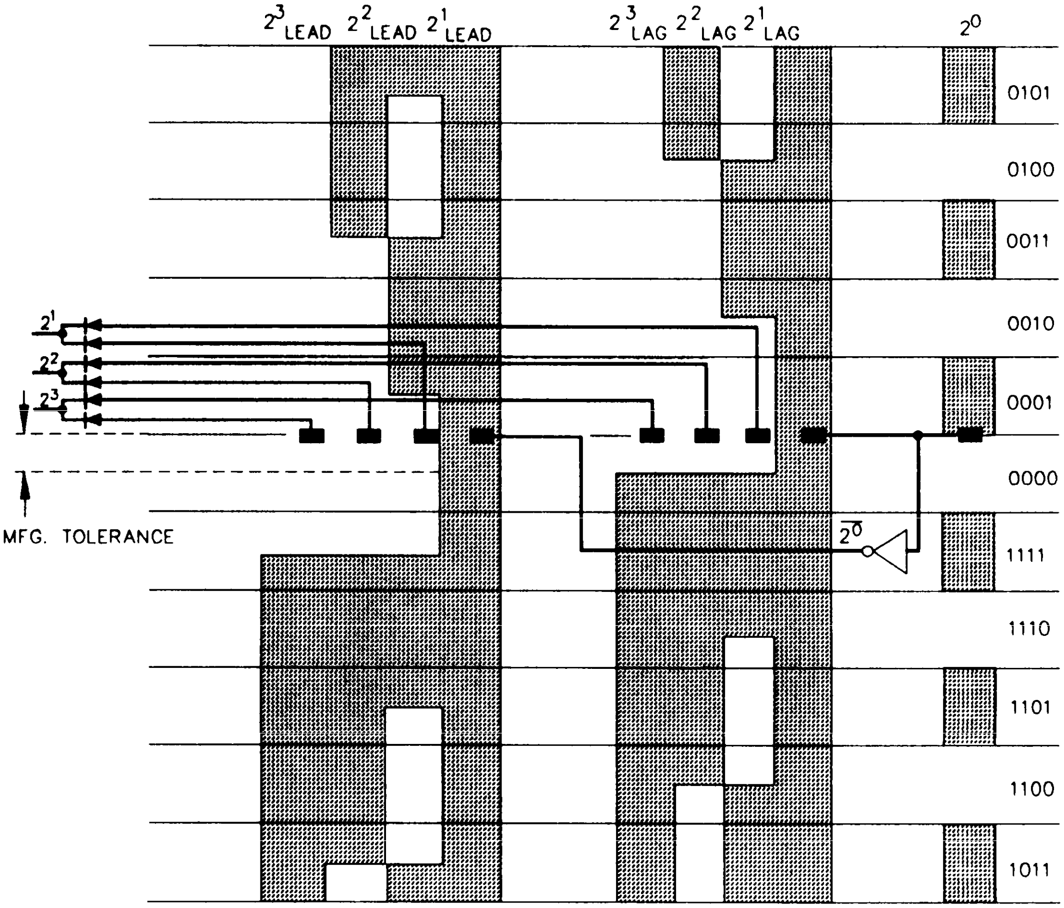


FIGURE 135. U-scan disc, single belt.

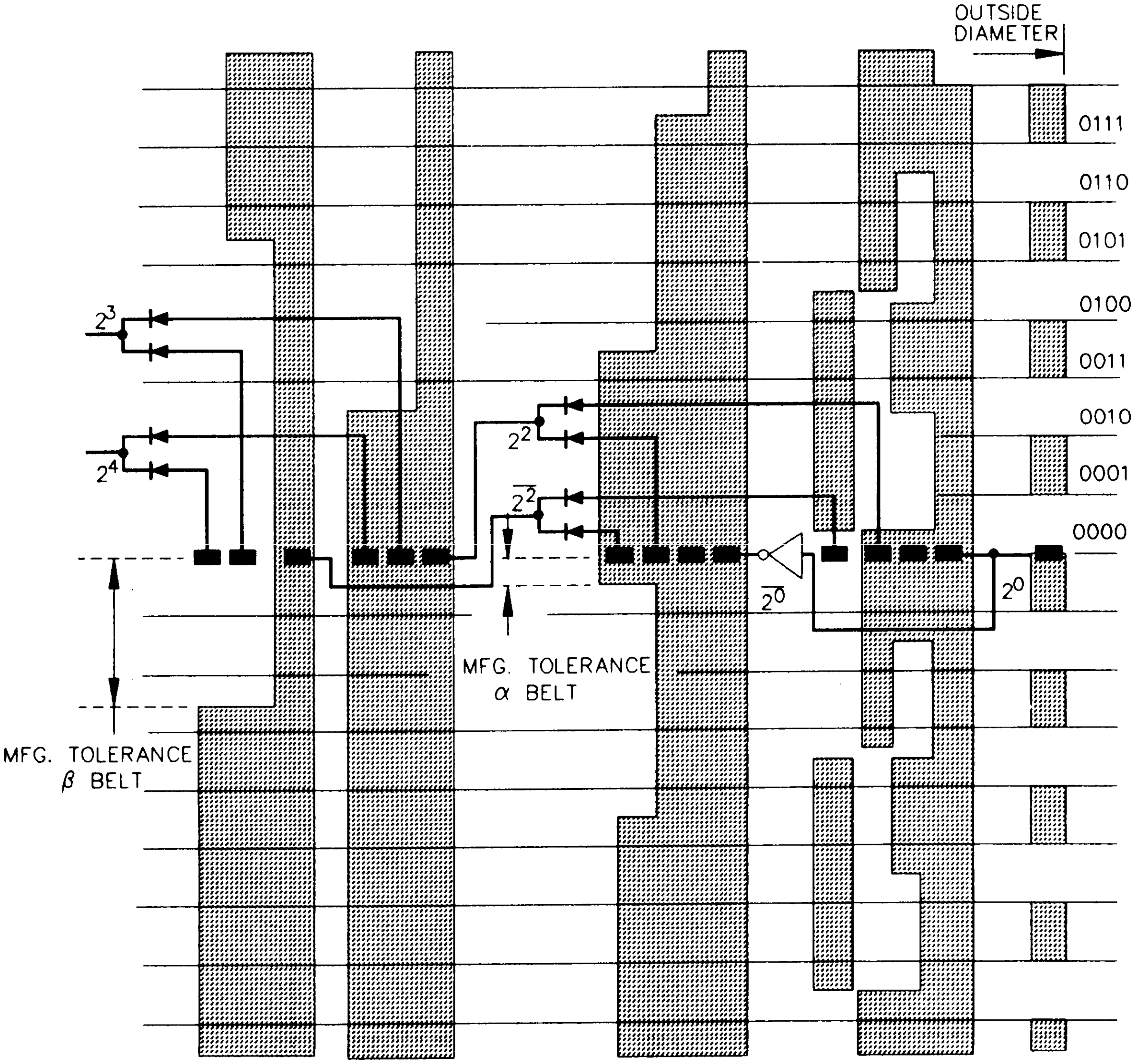


FIGURE 136. U-scan disc, dual belt.

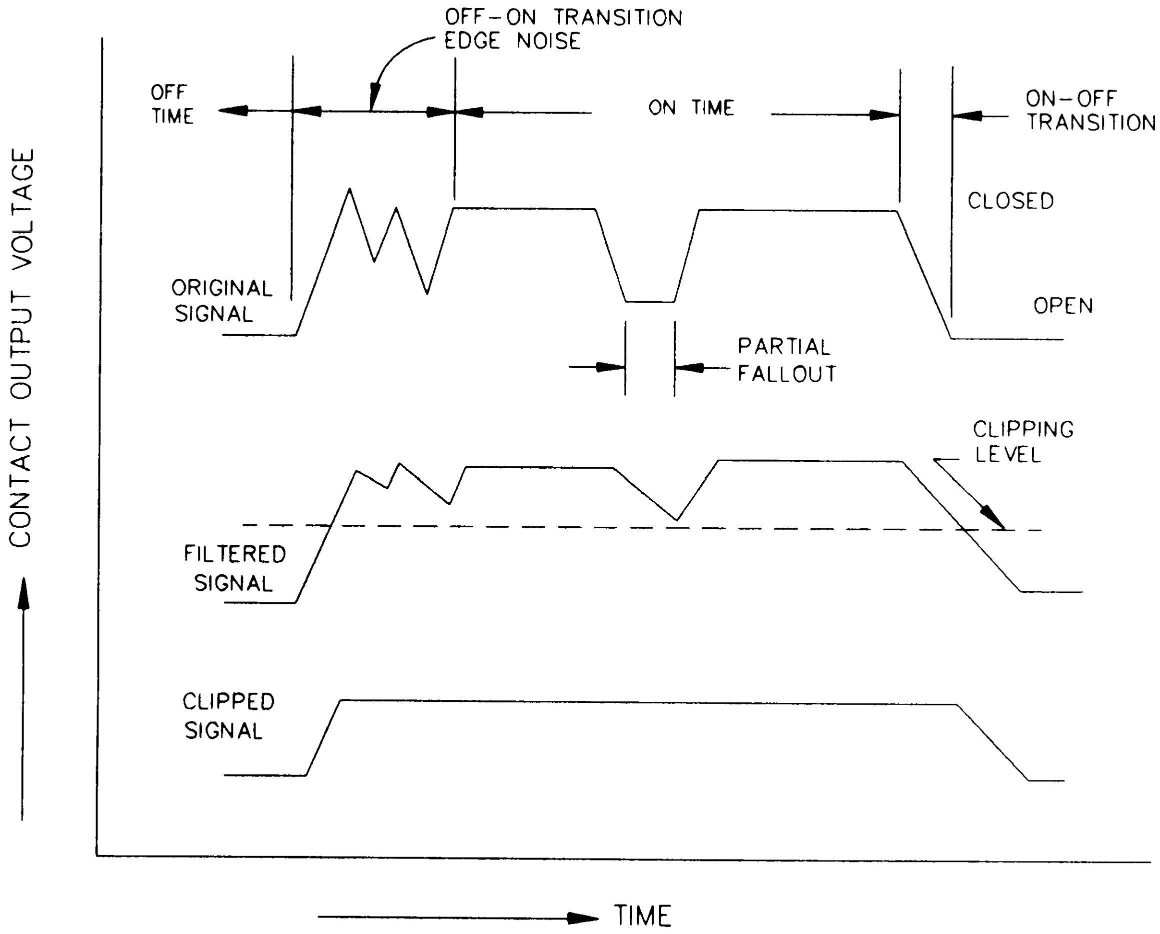


FIGURE 137. Signal-to-noise ratio improvement via simple clipper-filter techniques.

APPENDIX

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