AN INTRODUCTION TO
DELAY LINES BY COMPUTER DEVICES CORP.

LUMPED CONSTANT

MAGNETOSTRICTIVE

DISTRIBUTED

This paper provides a simple, non-technical presentation of the field of Delay Lines. Delay Lines of all currently popular types are described, simplified theories of operation are shown, applications are discussed and attainable characteristics are related to size and prices. It should be of interest to technical as well as non-technical personnel who deal in these versatile components.

Prepared for you by "Gene" Wendolkowski and "Ken" Dunne of CDC, who are always available to you for discussion of any Delay Line problems. Telephone Area Code 516 – AR 1-0666.

AN INTRODUCTION TO DELAY LINES BY COMPUTER DEVICES CORP.

With the increased popularity of radar systems, computers, and other digital devices, an ever-increasing demand for components that can give the designer time control over his pulse information has led to the popularity of various types of Delay Lines. In general Delay Lines are used wherever systems and equipments use electrical information related to time. Devices such as computers, guided missiles, radar systems of all types, identification coders and decoders, telemetering systems, navigation systems, pulse forming networks, color television all require Delay Lines to control the time position of information. They are used for such things as information storage, radar target cancellation, generation of precise timing pulses, signal compression and expansion, radar range marker generators, radar range calibration, etc.

At present, the popular type Delay Lines fall into two categories – the electromagnetic and the sonic Delay Lines. Electromagnetic Delay Lines are further designated by the type circuitry used, falling into three basic categories – the lumped constant Delay Line, the distributed constant Delay Line and the delay cable. The sonic Delay Lines fall into two categories – the magnetostrictive Delay Line and the solid ultra-sonic Delay Line (crystal type). Computer Devices Corporation, at this time, specializes in the design, development and production of lumped constant, distributed constant and magnetostrictive Delay Lines. We do not manufacture Delay Cable but occasionally on customer requirement purchase the cable, treat it, package it, terminate it and deliver a completed unit to the customer There are no plans in the near future to deal in the solid ultra-sonic type.

Delay Lines are made to give a fixed delay; they are tapped to provide a series of delays, and are made variable to provide either switch type, decade, or continuous variation of delay time.

Because applications of Delay Lines are so varied and because of the infinity of combinations of requirements that are used, Delay Lines are usually custom designed for specific applications. Although CDC catalogues specific units, these units are seldom purchased as shown in the catalogue sheets. The customer usually wants some variation which his particular equipment requires. CDC does stock standard components and is able to custom design and produce a unit in a matter of a week or two, depending on its complexity.

A Delay Line is basically a transmission line which, through circuitry or electromechanical means, has been compressed into a small volume. Its function is to delay information for a specific length of time, usually in the microsecond range.

In the electromagnetic type Delay Lines, where delay is obtained through the use of networks consisting of inductors and capacitors, the Delay Lines are governed by transmission line theory. Transmission line theory, in turn, is derived from filter theory as the number of sections approaches infinity. Therefore, a Delay Line has many of the characteristics of both a transmission line and of a filter. The distributed line more closely approximates a transmission line, and the lumped constant line more closely approaches a filter. A true transmission line has almost no degradation of signal frequencies up to hundreds of megacycles. As more delay is obtained for the same volume, the higher frequency response suffers. The greater the compression the lower the upper cut off frequency. In a distributed constant line, this compression is accomplished by increasing the delay per inch; in a lumped constant line by decreasing the number of sections. It is necessary to introduce phase compensation into the line to insure that all frequencies up to the cut-off are delayed equally. Insufficient delay of higher frequencies causes preshoot in the step response of the line. Since Delay Lines are normally used for step functions and square waves rather than sine waves, it is convenient to express the line in terms of the rise time (at the output) of a perfect step function introduced at the input. The relationship between (F) frequency response (3db Pts.) and rise time (tr) is expressed by the equation

$$F = \frac{.36}{t_r}$$

LUMPED CONSTANT DELAY LINES. The lumped constant Delay Line in its simplest form consists of a number of inductors and capacitors all similar in value (see Fig. 2). The inductors are connected in series and the capacitors are connected through the junction between the inductors to the ground lead. The number of inductor capacitor sections which are required to obtain a particular frequency response or delay (t_d) to rise time (t_r) ratio is represented by the empirical equation

$$n \cong \left(\frac{t_d}{t_r}\right)^{3/2}$$

This equation holds fairly well for ratios (t_d/t_r) up to 50 to 1. Higher ratios than this are obtainable in certain cases but in most cases are difficult because of the difficulty in obtaining the required "Q" for the coils. At CDC, complex sections, special powdered iron cores and novel construction are used to reduce the number of sections required to a basic minimum. The price of a lumped constant Delay Line is therefore closely related to the number of sections required. The cost per section is also influenced by the size of the inductor and the capacitors needed. Equations governing the inductance and capacitance required are shown below.

$C = t_d/Z_o$ $\quad$ C = Capacitance $\quad$ Z_o = Impedance
$L = t_d \times Z_o$ $\quad$ L = Inductance $\quad$ t_d = Delay Time

In the usual short delay Delay Line, the inductors are worth approximately 30¢ and the capacitors around 24¢. With factors introduced for wiring the unit, encapsulating, canning, etc., the cost per section approaches $1.00 per section in small quantities and approximately half that in large quantities. Where inductors are necessarily large, requiring the use of large toroidal coils, the coil form alone can cost $1.00 and the finished coil $2.50 or more. Capacitors for long Delay Lines like this sometimes run $2.00 and it is not uncommon to require a cost of $8.00 to $10.00 per section when Delay Lines in the audio frequency range are specified.

A Delay Line must also be built to match the operating impedance of the circuit with which it is to be used. It is necessary, therefore, at all times, to specify impedance for impedance governs the unit value of the

DELAY LINE TERMINOLOGY

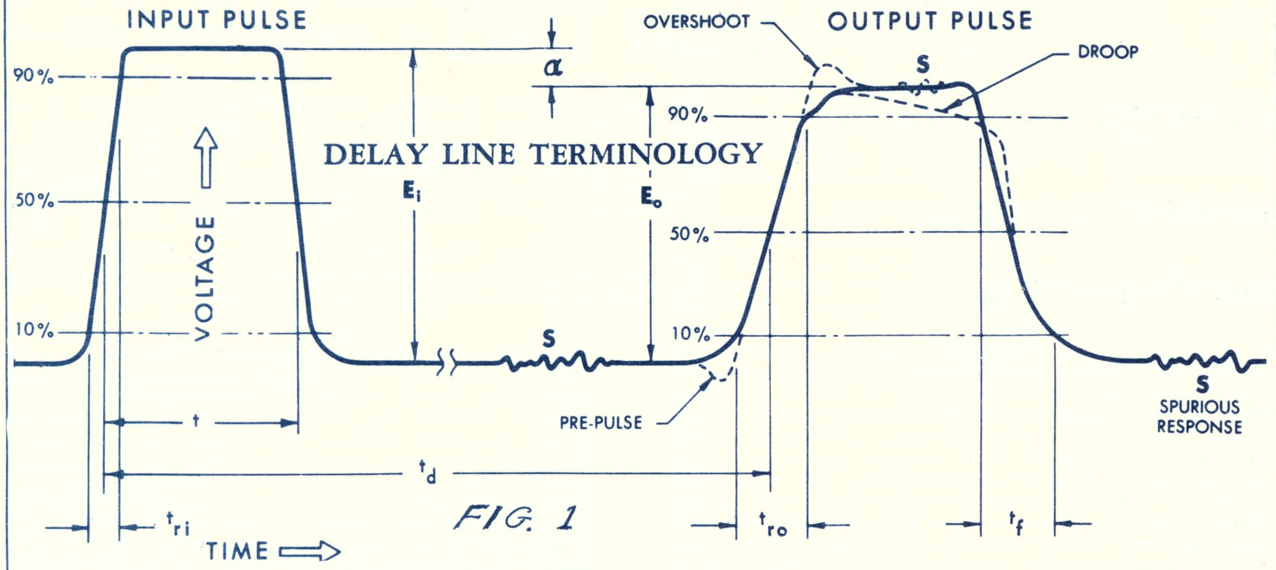

FIG. 1

t_{ri}	Input pulse rise time
t_{ro}	Output pulse rise time
t_r	Network pulse rise time = $\sqrt{(t_{ro})^2 - (t_{ri})^2}$
	Overshoot...A continuation of the leading edge of the pulse
	Droop...A sloping of the top of the pulse
t_f	Fall Time
α	Attenuation (in db) = 20 log E_i/E_o
S	Spurious Response - Distortion - Ripple... Three common terms used to define any irregularities in the signal output of the delay line due to various causes. This may be expressed as db below E_o
t	Pulse Width...Usually measured at 50% amplitude points.
t_d	Delay Time...The pulse delay is usually measured from the 50% amplitude point of the leading edge of the input pulse to the 50% amplitude point of the leading edge of the output pulse.
Z_o	Characteristic Impedance...That value of terminating impedance which provides minimum reflection to the input of the line.
t_d/t_r	Delay to Rise Time Ratio...The ratio of total delay to the delay line rise time is one measure of the quality of the delay line. (Figure of Merit)
	Bandwidth...Those frequencies which are passed at a useful amplitude (attenuated 3db or less, for example). This is related to rise time approximately by bandwidth x rise time = .36
	Temperature Coefficient...Usually expressed as a percentage change in delay per degree Centigrade or parts per million per degree Centigrade (PPM/°C).
	Phase Shift...Delay lines may be used as phase shifting devices. A delay line will shift the phase of a sine wave an amount in degrees equal to 360 x delay time x frequency of sine wave. $\theta = 360 \times t_d \times f$.

inductance and capacitance – therefore, the Delay Line price i.e., it is possible to reduce the impedance of a long Delay Line thus reducing the size of the inductance to a point where its price becomes nominal. Impedance also governs the ability to make certain Delay Lines, i.e., when high impedance is specified; from equation $Z_o = \sqrt{\frac{L}{C}}$ it is seen that large inductors and small capacitors are required; if the value of capacitance becomes too small, high response Delay Lines cannot be made due to stray capacitances influencing the proper LC balance.

Lumped constant Delay Lines can be made with very good temperature stability. Normal stabilities are about 40-50 PPM/°C and can be made as low as 5 PPM/°C. Delay accuracy also affects the price of a Delay Line. Accuracies of .05 us + 1% are normal and accuracies of .010 us + .1% are achieved for a price.

Lumped constant Delay Lines can be tapped at several points to give a series of delays. The number of such taps and the accuracy of the tapped delay also adds to the price of the Delay Lines. Lines can be tapped to an accuracy and spacing to two times the rise time of the Delay Line for a nominal cost and to .01+ .1% for a higher price.

The amount of permissible ripple on a Delay Line can also affect the price. Ripple is a function of impedance matching within the Delay Line, the number of sections of the line and external effects of the casing and construction on the Delay Line. Normal ripple is less than 10% of the output pulse amplitude. Ripple as little as .1% can be achieved by proper and careful construction. However, such a Delay Line would be very expensive.

Normally, CDC Delay Lines are made in very small packages consistent with the use of existing components which are available at low cost. Where extreme miniaturization is required, CDC uses sub-miniature components and is able to achieve miniature size unsurpassed by any other manufacturer. Prices of miniature units are naturally higher than normal units.

At CDC, the lumped constant Delay Lines are made to meet military specifications. Most are hermetically sealed in metal containers, they are usually resin encapsulated with a foam material. They are built to withstand the shock and vibration of military requirements.

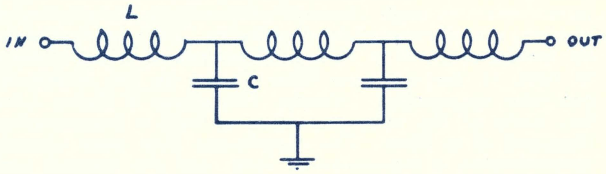

FIG. 2

Lumped constant Delay Lines having delays from .01 us to 100,000 us are made at CDC, and delay to rise time ratios up to 170 to 1, impedances from 20 to 20,000 ohms are available. The size of lumped constant Delay Line depends on the delay to rise time ratio and the total delay of the Delay Line.

DISTRIBUTED CONSTANT DELAY LINES. Distributed constant Delay Lines more closely approximate the transmission line. They are made by winding a continuous coil (usually multi layer) on a glass or ceramic rod that has been coated with a conductive material such as silver to provide a ground conductor pattern. This rod is covered with a thin layer of dielectric such as Polystyrene, Teflon, or Mylar. The coil provides a continuous inductance along the rod and the capacitance is obtained between the coil wire and the ground plane. (See Fig. 3)

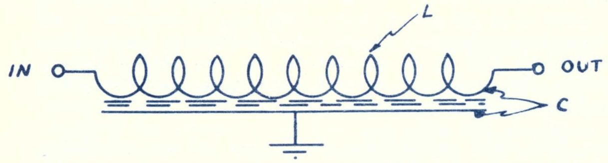

FIG. 3

Distributed constant lines are limited in their delay to rise time ratio and generally do not exceed a delay to rise time ratio of 10 to 1. They are also poor in respect to temperature, having a coefficient of delay of 150 PPM/°C normally, and 100 PPM/°C at best.

To attain a 10 to 1 delay to rise time ratio, a distributed constant Delay Line winding must be at least 6" long. Delays of up to 5 us can be achieved with one 6" winding. Longer delays in shorter windings can be attained but at the sacrifice of the delay to rise time ratio. Distributed constant Delay Lines may be cascaded to obtain longer delays. Not all impedances are possible for every delay because of the limitation of the amount of capacitance that can be attained from the area of the winding. At CDC special techniques allow us to stretch the above limits a slight amount, however, this affects the price.

The same basic equations for L and C, as shown above, apply to distributed constant lines. The C is the total capacitance between the coil and the ground plane.

Distributed constant Delay Lines are nominally priced. the usual 10:1 (t_d/t_r) stick line, housed in a 3/8" x 3/8" x 6" case, will cost approximately $15.00 for a single unit, and $3.00 to $4.00 in large quantities. These units are also built to meet military specifications and are generally epoxy encapsulated.

DELAY CABLE (not manufactured by CDC.) Delay cable is basically a distributed constant Delay Line but with a much longer winding. Consequently, delay per inch is very small. Delay cables, depending on the method of manufacture provide very good frequency response but have the same shortcoming as distributed lines as far as temperature is concerned. They also have very high attenuation of signal associated with them. As stated above, on customer request, CDC packages and trims delay cable, when requested.

MAGNETOSTRICTIVE DELAY LINES. Magnetostrictive Delay Lines, in effect, reduce the velocity of an electrical wave by converting it into a sound wave and then reconverting it back into its electrical form. The simplest magnetostrictive line (figure 4) consists of an input transducer coil with a magnetostrictive core attached to a wire sonic waveguide. The far end of the sonic waveguide is attached to a similar output transducer. The magnetostrictive effect refers to the fact that if a magnetic field is applied to a sample of magnetostrictive material, parallel to its length, it will undergo a change in length. The inverse magnetostrictive effect refers to the fact that if the sample is subjected to a mechanical strain while biased in a magnetic field there will be a change of flux in the sample. At the input transducer, flux change in a coil creates a mechanical stress in the magnetostrictive core which travels down the waveguide wire as a sound wave. When the wave reaches the output transducer, it alters the permeability of the magnetostrictive core which is polarized by the permanent magnet. The resulting flux change induces an electrical signal in the output coil. Acoustic absorbers at each end of the magnetostrictive line prevent signal wave reflections.

FIG. 4

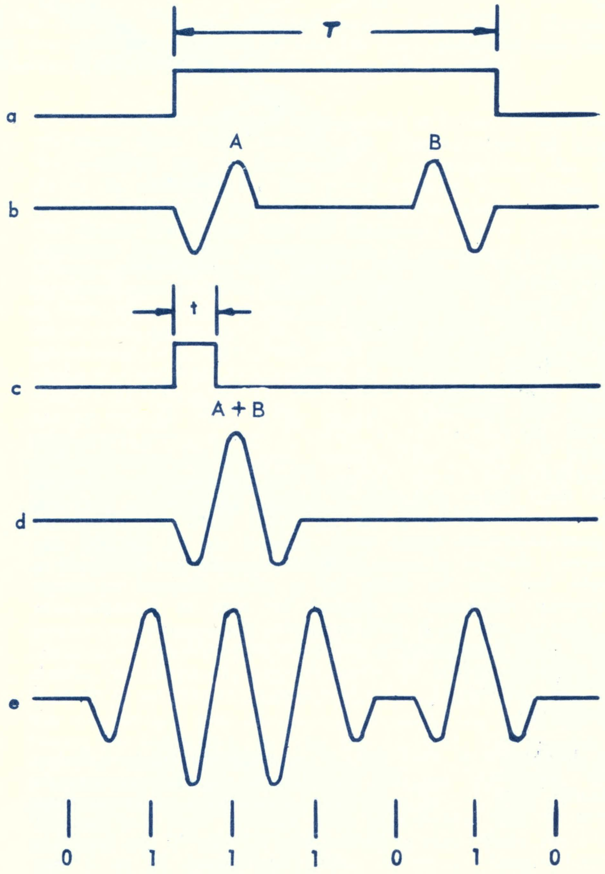

FIG. 5

Output wave forms are determined by the duration of the input pulse. In figure 5a the input pulse duration t is appreciably longer than the time taken for a strain pulse to travel the line one transducer coil length. This produces an output voltage as shown in figure 5b. In figure 5c, the duration of the input pulse is less than or equal to t. This produces an output pulse, as shown in figure 5d. This output is formed by the positive portions A & B of figure 5b forming a single positive peak. It is this coalesced positive peak which is used in systems operating in a digital fashion. Input pulse width width t can be adjusted to an optimum for the Delay Line and the given pulse spacing. When the Delay Line is adjusted for the optimum digital rate, a typical random pulse output pattern for a code of 0-1-1-1-0-1.0 is shown in figure 5e.

The magnetostrictive Delay Line shown in figure 4 makes use of longitudinal sound waves, i.e. waves in which particle motion is in the same direction as wave motion. It is useful in low to medium delay bandwidth applications and can be readily tapped. To make a longer Delay Line, the wire waveguide must be coiled to fit a reasonable space. However, when this is done the signal is distorted considerably. The arrangement shown in figure 6 provides maximum delay without distortion – consequently higher bandwidth. It consists of the usual sonic waveguide and transducer. This time the transducers are joined to the waveguide at right angles and are connected so that they provide and respond to a torsional wave in the wire. The torsional waves travel with negligible distortion down the waveguide wire. Torsional waves also travel slower down a waveguide; whereas in the longitudinal mode the delay per inch of waveguide wire is approximately 5 usec, in the torsional mode the delay per inch is 9 usec.

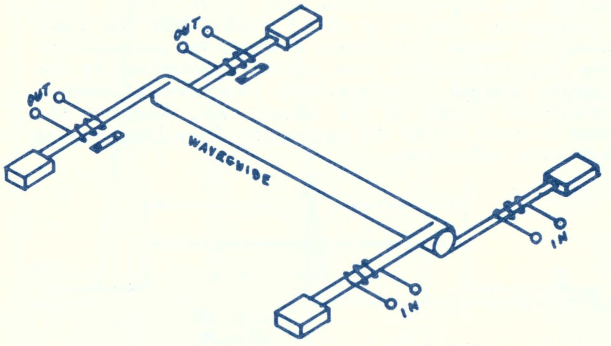

FIG 6

Magnetostrictive Delay Lines are extremely useful where pulse information or trigger information requiring long delays is involved. They are not generally used in applications where the shape of the pulse has to be preserved. Due to the fact that they are converting energy from electrical to mechanical and back to electrical, considerable attenuation of the signal is experienced. An insertion loss of -50 to -70 db can be expected. Magnetostrictive Delay Lines provide very long delays in very small space, and digital operating frequencies up to 5 megacycles. They are capable of having their total delay and tapped delays adjustable; they are extremely stable with temperature. CDC manufactures magnetostrictive lines with delays up to 20,000 us, however, delays of over 10 milliseconds are difficult to obtain but can be done for a price. Normal maximum frequency response or digital bit rate is 1 megacycle for delays up to 7 milliseconds. Frequency responses higher than 2 megacycle are still somewhat of a laboratory novelty except for short delays (20 to 30 us) which can be produced with frequency responses of up to 5 megacycles.

The temperature stability of a magnetostrictive Delay Line depends on the stability of the wire waveguide material. With normal materials, stabilities of better than 5PPM/°C are attainable; with special care and special heat treat, stabilities of better than ½PPM/°C are feasible Normal signal to noise ratios run about 10 to 1 but 20-30 to 1 can be provided. impedances of input and output transducers from 50 to 3,000 ohms are available.

Short delay longitudinal lines are generally packaged in long, slim packages. A normal package would be 3/8" x 1" in cross section with length dependent on the delay required. A 20 us Delay Line will be 7" long. Greater delays will increase the length by 1" for every additional 5 us. Long delay torsional Delay Lines are housed in flat, square packages. A normal package for delays up to 3,000 us would be 6½" x 7½" x ½". All fixed Delay Lines are provided with a small delay adjustment, usually a swing of 3 us. Pricing depends on frequency response, temperature stability and signal to noise requirements. Longitudinal lines are sold for approximately $100 in single quantities and down to $20 to $30 in large quantities. Torsional lines bring between $150 and $300 for single quantities and are priced as low as $50 to $80 in quantity. Most magnetostrictive Delay Lines are made to meet military requirements and are housed in hermetically sealed metal containers. They are built to withstand shock and vibration as required.

<u>SOLID ULTRA-SONIC DELAY LINES.</u> (Not manufactured by CDC.) Solid ultra-sonic Delay Lines operate basically on the same principle as magnetostrictive Delay Lines. Here usually a block of fused quartz is used as the delay medium. Piezoelectric transducers are cemented to the quartz at the input and output extremities of a pre-determined delay path. An electrical signal applied at the input transducer creates a mechanical vibration. This vibration is propagated along the delay path until it reaches the output transducer. At this point the vibration is transformed again into an electrical signal. Information carried by this signal is delayed in time by an amount dependent on the length and nature of the delay medium. Spacesaving is accomplished in this type of Delay Line by the use of a folded path where the beam is reflected off the sides of the quartz blank, in this manner allowing longer delays in smaller blank size. Solid ultra-sonic Delay Lines are capable of operations at much higher frequencies than magnetostrictive lines. However, their temperature coefficient is quite poor (-70 PPM/°C). They are not as rugged and are much bulkier.

<u>VARIABLE DELAY LINES.</u> CDC makes variable Delay Lines using the three types that we manufacture. Where high delay to rise time ratios are required, lumped constant Delay Lines are used and are tapped with the taps being attached to an appropriate switch. A standard rotary variable Delay Line configuration is shown in our catalogue sheet (V108, 150 etc.) wherein a 60 position shorting type commutator switch is used, thus providing a 120 to 1 resolution for the Delay Lines. Variable Delay Lines with decade type switching are also constructed.

There are also applications wherein a tapped Delay Line cannot be used — because the impedance at the tap must be at least 10 x the impedance of the line. For cases like this, CDC manufactures an insertion type variable Delay Line. Here each delay setting is a complete Delay Line so that external load can be at the impedance of the Delay Line as opposed to a tapped line where the load impedance must be very much higher than the characteristic impedance of the Delay Line to avoid undesirable reflections.

Where higher resolution is required, lumped constant Delay Lines are built, using a continuous solenoid coil with a wiper arm wiping along the coil, thereby providing a tap with a resolution equivalent to the total number of turns of the coils in the entire Delay Line. These lines are usually packaged in long narrow containers and use a lead screw delay adjustment shaft (V176 & V172).

Distributed constant variable Delay Lines are made in a manner similar to the high resolution lumped constant Delay Line, except that the capacitance is again attained in the same manner as described for the distributed constant line above. However, distributed constant variables suffer from the same limitations in temperature coefficient and limited (t_d/t_r) as distributed lines as previously mentioned.

Magnetostrictive Delay Lines are made variable simply by making either the input or output transducer mechanically movable. However, all variable magnetostrictive lines must be made using the longitudinal mode.

Short delay variables are made using a lead screw type adjustment and have a configuration similar to the distributed constant variables described above. Long delays are attained in much the same manner as multi turn potentiometers wherein the delay wire is wound into a helical form and the transducer is moved over the entire wire length in several turns of the control shaft. All ranges from 5 to 5000 usec are made. Because these lines use the longitudinal mode, lines with delays over 100 usec are subject to periodic pulse phase reversal; consequently, special output circuitry to eliminate this effect is necessary. Overall accuracy of line and circuitry is better than 0.2%. Variable magnetostrictive lines are finding wide application in range and delay calibration devices because they are compact, passive and capable of high reliability.

As the field of Delay Lines grows and requirements become more stringent, and more demanding, the ingenuity of the Delay Line designer plays an important part and should be utilized by the customer when designing new equipments. Many new developments are currently being undertaken at CDC and as their feasibility is proven, bulletins will be issued and sent to the recipients of this paper.