Development of Instrument for Non-Destructive Measurement of Concrete Pavement Thickness

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Research Study 61-1 F

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Measurement of Concrete Pavement Thickness
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ABSTRACT

A nondestructive test method for measuring the thickness of concrete pavement is sought in the interest of economy and to eliminate coring and associated structural damage.

A study of such a device using ultrasonic waves is described. A simplified discussion of ultrasonic wave phenomena preceeds a general description of the electronic equipment used in this project. Since much of the difficulty of building such a device was found to lie with transducer development, a detailed explanation of the author's progress in this direction is given.

Ultrasonic waves of approximately 80,000 hertz were transmitted into the concrete and reflections from the pavement-base interface were received and displayed on an oscilloscope. However, no practical instrument has yet been perfected.

RESEARCH PROBLEM STATEMENT

A reliable, non-destructive method for the determination of the thickness of concrete pavement is highly desirable to eliminate structural damage during testing, to shorten testing time, and to promote economy.

OBJECTIVES

It is proposed to develop an electronic instrument employing mechanical vibrations of ultra-sonic frequency, which will indicate the thickness of concrete pavement.

An electrical pulse from the transmitter is to be fed into the sending transducer. The transducer will convert this pulse into an ultrasonic mechanical wave and couple this wave into the concrete. The wave will be reflected from the pavement-base interface and will return to the pavement surface. There, a receiving transducer will convert the received signal into a corresponding electrical signal. This signal will be displayed on an oscilloscope as a graph of received signal amplitude versus time. For a constant wave velocity, the time scale will correspond to distance traveled and may be so calibrated.

CONCLUSIONS

Although longitudinal waves were reflected and received from the bottom of a concrete slab five inches in thickness, a practical instrument was not perfected.

Several major problems remain. The primary one is that the low amplitude of the received signal makes it difficult to measure its time of travel. Two solutions seem to be the most promising. One is to improve transducer effectiveness and efficiency. The other is to shorten the transducer ringing time enough to permit single transducer operation.

Another solution is to use more sophisticated electronics to determine the waves presence and time of travel. Such a device would be a cross-correlator which compares all received signals with a representation of what is expected to be received. An output shows the degree of alikeness or correlation.

Before entering into a discussion of the investigation, it is necessary to provide definitions of the terms to be used and to present a resume' of ultrasonic theory to the extent that it is involved in this work. Theory, transducer design, and general experimental procedures are presented in some detail in order that future investigation may take advantage of what has been done here.

BASIC ULTRASONIC THEORY

The word ultrasonic refers to mechanical vibrations and waves higher in frequency than those to which the human ear normally responds. The frequencies usually are considered to be those above 20,000 hertz (cycles per second). Only a few individuals actually hear some of these waves but many animals, birds, and insects hear sound in parts of the ultrasonic region.

It is important to realize the difference between mechanical and electromagnetic (radio) waves. Although they may have the same frequency, they are different forms of energy. The human ear responds to mechanical waves but not to radio waves whose frequency is low enough to be the same as a sound wave. Likewise, a radio does not respond to mechanical waves no matter what their frequency. As an example, the ear does not hear the very common 60 hertz radio wave field from the house wiring. It may hear vibration caused by the magnetic field's action on a transformer or ballast part, but this is mechanical energy.

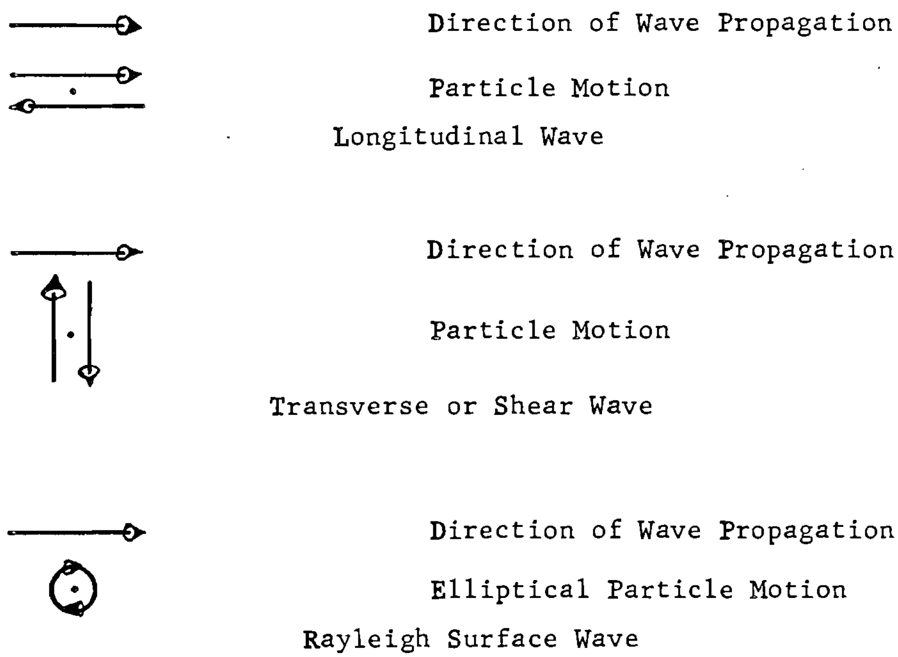


Figure I. Particle Motion for Various Modes of Wave Propagation

Ultrasonic waves, once generated, propagate through a medium by one or more of several modes of travel. In all of these modes the wave is transmitted by small movements in the structure of the medium. The particles of the structure are displaced elastically by a very minute amount. Longitudinal mode of wave motion is transmitted when the particle movements are in the same direction that the wave is being propagated. This is the mode which is commonly explained as a series of compressions and rarefactions in the transmitting medium. Transverse waves (shear waves) are set up when the particle movement is perpendicular to the direction of propagation. It should be noticed that shear waves are polarized; that is, the plane of the particle movement in a homogenous medium is constant for a continuous wave. Rayleigh surface waves are transmitted by elliptical particle motion along and near the surface.

The plane of motion is normal to the surface and parallel to the direction of propagation. Rayleigh waves usually occur in a medium whose thickness is greater than one wavelength. In thinner sections, other types of complex surface waves (Lamb waves and Love waves) may be set up; however, they are not involved in this research due to the thickness of the slabs under test.

The velocity with which the particle movement transmits the wave is a function of the elastic constants of the medium. There are well defined relationships between these elastic constants and the velocity of longitudinal and shear waves. Empirical relationships have been found for these constants and the velocity of Rayleigh surface waves. By measuring accurately the appropriate wave velocities, the elastic constants of a material can be computed.

A concept called wavelength was mentioned earlier. The wavelength is the distance the wave front travels during one complete cycle. It is calculated by dividing the wave velocity by the frequency. Note that each type of wave has its own particular wavelength.

Ultrasonic waves, when transmitted from one medium to another may be totally reflected, totally transmitted, or some of both. The amount of energy to be reflected, or transmitted, is determined by the ratio of each medium's characteristic acoustic impedance. Acoustic impedance is the product of the wave velocity, usually that of the longitudinal wave, and the density of the medium. It is a measure of the material's resistance to deformation for a given force.

The reflection and transmission coefficients are simplest when the wave is transmitted normally into a medium. Assuming perfect acoustic contact between two flat surfaces the relationships are as follows:

$$\frac{Wr}{Wi} = R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

$$\frac{Wt}{Wi} = T = \frac{4\ Z_1 Z_2}{(Z_2 + Z_1)^2}$$

$$\text{and } R + T = 1.0$$

where:

Wi - Incident energy

Wr - Reflected energy

Wt - Transmitted energy

R - Reflection coefficient

T - Transmission coefficient

Z_1 - Acoustic impedance of the first medium

Z_2 - Acoustic impedance of the second medium

Due to the high impedance ratio involved, ultrasonic energy does not couple well into air from most materials. In most ultrasonic applications, a complete exclusion of air between two media is not practical without the use of a liquid interface; such as, oil, glycerine, water, or mercury.

TABLE I

RELATIONSHIPS BETWEEN THE ELASTIC CONSTANTS AND VARIOUS WAVE VELOCITIES

$$V_L = \sqrt{\frac{E}{\rho} \frac{(1 - \sigma)}{(1 + \sigma)(1 - 2\sigma)}}$$

$$V_T = \sqrt{\frac{E}{\rho} \frac{1}{2(1 + \sigma)}}$$

$$\frac{V_T}{V_L} = \sqrt{\frac{(1 - 2\sigma)}{2(1 - \sigma)}}$$

$$\frac{V_R}{V_T} = \frac{0.87 + 1.12\sigma}{1 + \sigma}$$; Bergmann Approximation

V_L - Longitudinal Wave Velocity

V_T - Transverse (Shear) Wave Velocity

V_R - Rayleigh (Surface) Wave Velocity

E - Young's Modulus of Elasticity

ρ - Density

σ - Poisson's Ratio

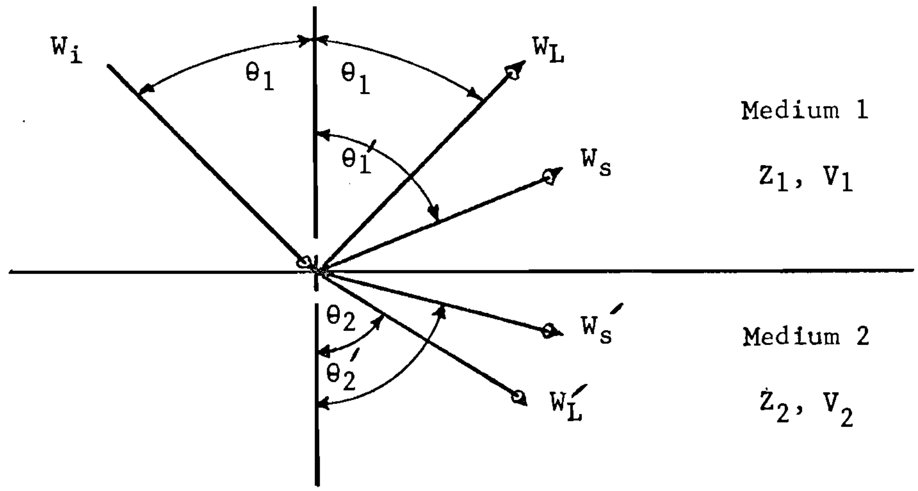
The calculation of the energy transmitted into the second medium must take into account reflections and transmissions at both liquid-solid interfaces. When the coupling layer is less than one wavelength thick, additional factors due to wave interference must be taken into account to calculate completely what is happening. If the layer is very thin, such as a thin layer of oil, it usually is ignored in all but the most exact calculations. The most efficient coupling layer may be shown to be one half wavelength thick with an acoustic impedance, Z_c, where $Z_c = \sqrt{Z_1 Z_2}$, Z_1 and Z_2 being the impedances of the two media to be coupled together.

If the surfaces of the interface are not smooth but are rough, not all waves will enter or leave normal to the surface. The result is refraction of the wave and various wave mode conversions. Snell's law of refraction may be used to calculate the angles of refractions. The equations may be written as:

$$\frac{\sin\theta_1}{V_1} = \frac{\sin\theta_2}{V_2}$$

where θ_1 and θ_2 are the angles of incidence and refraction in the appropriate media, V_1 and V_2 are the velocities.

It should be noticed that the acoustic impedance does not enter into the calculation of angles of refraction. Amounts of reflected and transmitted energy are functions of acoustic impedance ratios and angles of incidence and refraction. The impedance ratio does not determine whether the energy is transformed as the same wave type or is converted to some other form.



W_i - Incident Longitudinal Wave Energy
W_s - Reflected Shear Wave
W_L - Reflected Longitudinal Wave
W_s' - Refracted Shear Wave
W_L' - Refracted Longitudinal Wave

Figure II. Reflection & Refraction with Mode Conversion

Since the above equation does not consider mode conversion it must be modified. An expanded version could be written as:

$$\frac{\sin\theta_1}{V_L} = \frac{\sin\theta_1'}{V_t} = \frac{\sin\theta_2}{V_L'} = \frac{\sin\theta_2'}{V_t'}$$

θ_1 - Angle of incidence and reflection for incident and reflected longitudinal wave in medium 1.

θ_1' - Angle of reflection of shear wave in medium 1.

θ_2 - Angle of refraction of longidutinal wave in medium 2.

θ_2' - Angle of refraction of shear wave in medium 2.

V_L - Longitudinal wave velocity - medium 1.

V_L' - Longitudinal wave velocity - medium 2.

V_t - Shear wave velocity medium 1.

V_t' - Shear wave velocity medium 2.

Calculation of the energy levels involved in all waves, reflected and refracted, involves a series of equations containing the various angles just defined, wave velocities, acoustic impedances, and the elastic constants of the two media. These equations were worked out by C. G. Knott and published in 1899. They are only mentioned here since the calculation of absolute energy levels was considered unnecessary.

If a wave velocity in the second medium is higher than in the first medium, a "critical angle of incidence" may be determined for which the angle of refraction is 90^{o}. For angles of incidence greater than this the incident wave will be totally reflected. This critical angle, θ_c, is equal to:

$$\theta_c = \text{arc sin } (V_1/V_2), \text{ where } V_2 > V_1.$$

Another factor to be considered is attenuation of the transmitted waves. All materials will attenuate the wave, some much more than others. If a material is not homogeneous, the attenuation may vary within the material. Concrete is such a material. Attenuation loss may be considered to be of two types which occur together; i.e., frictional losses and scattering losses.

The frictional loss occurs because a finite amount of energy is required for particle motion, no matter how small the movement. As the wave is propagated, these losses can total up to a large percentage of the original wave. The nature of the transmitting medium determines how much energy is absorbed.

TABLE II

ULTRASONIC PROPERTIES OF MATERIALS

Material	Density lb/ft^3	Velocity, V_L ft/sec	Acoustic Impedance, Z lb/ft^2-sec x 10^6
Neoprene Rubber	82.9	5,250	0.44
Lucite	73.6	8,790	0.65
Steel, Mild	489.4	19,550	9.57
Aluminum	168.3	21,050	3.54
Copper, Annealed	556.7	15,610	8.69
Glycerol	78.5	6,245	0.49
Castor Oil	60.41	4,845	0.29
PZT-4	467	13,330	6.23
Lead	705	4,030	2.8

Scattering is the process by which the wave is reflected, refracted, or both within the transmitting medium. It will occur when any dimension of the grain structure of the medium begins to approach even a small fraction of a wavelength. When the medium is nonhomogeneous, such as concrete, scattering can be reduced only by increasing the wavelength. This will make the relative size of the components' interfaces (aggregate of many sizes and cement paste) smaller, and will reduce their ability to affect the ultrasonic beam.

EQUIPMENT DEVELOPMENT

Transmitting System:

The transmitter serves the sole purpose of delivering a pulse of controlled amplitude, length, and shape to the sending transducer. A number of ways to generate these pulses are known and are in everyday use. Much commercial equipment which is capable of doing an excellent job is on the market.

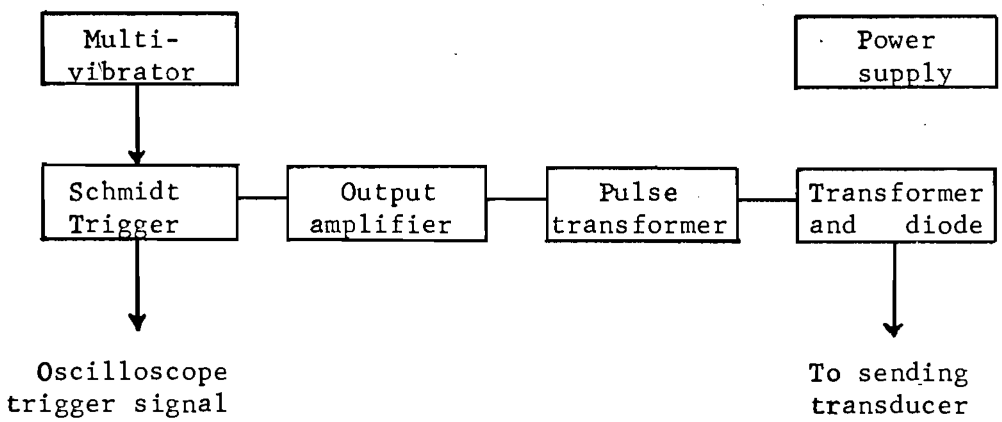


Figure III. Block Diagram of Transmitter System

A block diagram of the transmitter is shown in Figure III. A transistor multivibrator operates at 100 hertz. This frequency was chosen because it is rapid enough to give an essentially continuous indication on the oscilloscope readout, but is slow enough to allow the signals and their echoes to die out completely before the next pulse is transmitted.

The multivibrator output is differentiated to produce a short pulse. This pulse then triggers a tube type Schmitt Trigger circuit. A tube was chosen in order to obtain a voltage swing high enough to drive the final amplifier into conduction. The final amplifier tube remains cut off until the postive pulse from the Schmitt Trigger drives it into conduction. Output is transferred by a ferrite core pulse transformer into a 50 ohm coxial cable transmission line. In the transducer assembly, another pulse transformer raises the voltage back to a value satisfactory to drive the sending transducer. Peak voltage on the transducer is about 500 volts.

Few design changes have been made in this system since its initial construction. The original power supply operated from a storage battery and had inadequate power output. A new supply, operating from the power lines, was built. Values in the Schmitt Trigger circuit and output amplifier were adjusted to produce an output pulse of about one microsecond in duration.

Several different pulse transformers have been constructed to match the changing characteristics of the transducers as they were developed. A silicon diode was added across the secondary side of the final pulse transformer. The polarity of the diode is such that it allows the pulse to reach the transducer but shorts out all reverse polarity signals. This aids transducer damping by effectively eliminating every half cycle of oscillation as the transducer tends to ring.

A timing pulse is also supplied to the oscilloscope in the receiver.

Receiving System:

The receiving equipment consists of a preamplifier and a Hewlett-Packard 120B Oscilloscope.

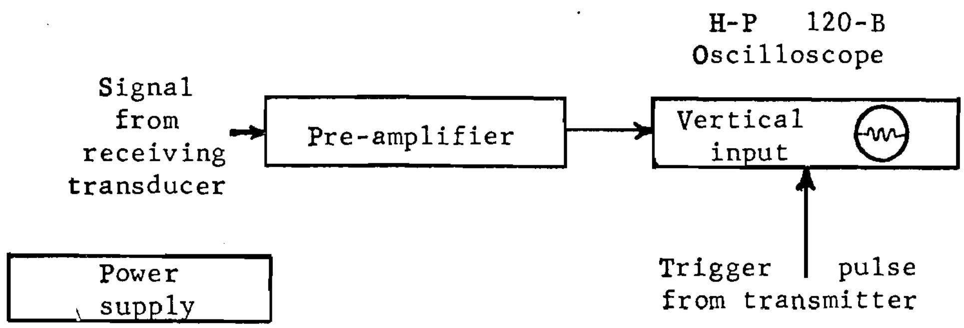
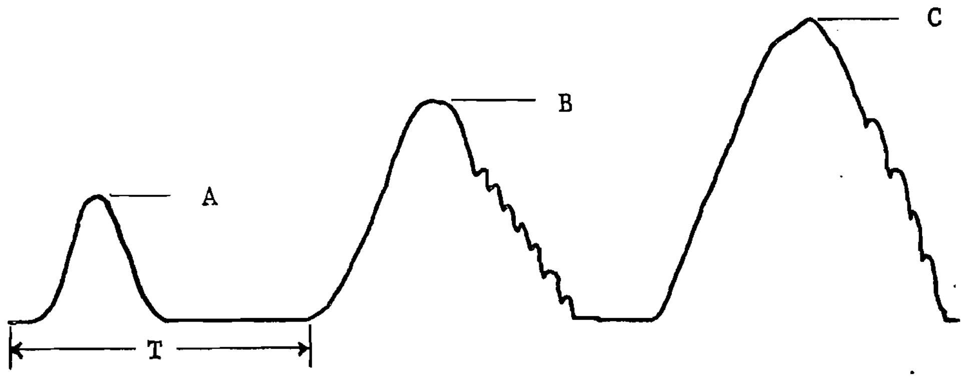


Figure IV. Block Diagram of Receiver System

The receiving transducer's output is first amplified by a preamplifier to a level the oscilloscope may use. Some trouble was experienced with the self generated noise of the preamplifiers obscuring received signals. Several low noise designs were built and used. Noise level ceased to be a problem only when the transducer development proceeded enough to raise the efficiency appreciably.

The oscilloscope receives the preamplifier output through the vertical input terminals. Horizontal input is an internally generated, highly accurate signal which varies linearly with time. Thus the display is a graph of the received voltage amplitude versus time. The time signal may be varied to different values for ease of time measurements. The timing pulse from the transmitter triggers the display each time a pulse is transmitted. This is the type of presentation known as A-Scan.



T - Concrete Thickness
A - Feedthrough Pulse to Indicate Transmitter Output (Start of Sweep)
B - Received Reflected Longitudinal Wave
C - Received Rayleigh Wave

Figure V. Typical A-Scan Oscilloscope Display Showing Signals Received

Some preliminary investigation of the electronics required for a single transducer system were made, but the system was not built due to the lengthy ringing time in the transducers. One such system consists of tying the transmitter, transducer, and receiver directly together. In this system, the receiver is overloaded by the transmitter pulse and requires a finite amount of time to recover sufficiently to operate properly. Another method uses an electronic arrangement to switch the transducer to the transmitter for a pulse and then back to the receiver to display the return echoes.

Transducers:

The ultrasonic transducer is a device for converting ultrasonic wave motion of one energy form into that of another energy form. In this research, the transducers convert mechanical energy into electrical energy and vice versa. Ultrasonic transducers usually employ either magnetostrictive or piezoelectric (electrostrictive) materials in their construction, although there are other ways to generate ultrasonic and electrical waves.

Magnetostrictive transducers made use of the property of some materials of changing dimension when in a varying magnetic field. Materials having this property include iron, nickel, cobalt, and various of their alloys. The necessity for a magnetizing coil, its inherent size and power loss and eddy current losses in the magnetostrictive element, usually restrict this type of transducer to high power uses in the lower portion of the ultrasonic region.

Piezoelectric transducers use the property of some crystalline materials of changing dimension when in varying electrostatic (voltage) field. This phenomenon is reversible, although the efficiency is not the same in either direction. The crystal phonograph cartridges are examples of piezoelectric transducers, although they are not ultrasonic. They produce an electric signal corresponding to the needle vibration.

There are many materials which possess piezoelectric properties. Until recent years, the choice usually represented a compromise between low efficiency, a tendency to fail when hot, and even solubility in water.

Newer materials have removed most of the objectionable qualities. Some commonly used piezoelectric materials are quartz, barium titanate, lithium sulfate, and lead zirconate titantate. High voltages are required to generate high power levels, but the electrical danger may be minimized by the use of excellent insulators such as teflon and the polyvinylchorides.

Many problems arise in transducer design. First a choice must be made between magnetostrictive or piezoelectric materials. With the great improvement in piezoelectric materials and their fabrication, they have become very widespread in use. Final design must take into account sensitivity both as a driver and receiver, frequency of operation and bandwidth (range of frequencies around center frequency), impedance matching, damping and its effect upon sensitivity and ringing time (the transducer's tendency to continue oscillation once excited), power levels and internal heating, beam directivity, and the manner of housing.

In the design, a linear analysis was used. This assumes that the system operates completely within the elastic range of all components. At the low power levels used here, this is a valid assumption. If it were not, component failure eventually should result.

A decision was made to use a piezoelectric transducer because of the ease of transducer construction and design and associated transmitter design. Several discs of a lead zirconate titanate, Clevite PZT-4, were purchased. These were one half inch in thickness and one inch in

TABLE III

PROPERTIES OF VARIOUS TRANSDUCER MATERIALS

Transducer	Receiving Constant $(10^{-3})\ \frac{V/m}{N/m^2}$	Transmitting Constant $(10^{-12})\ \frac{m/m}{V/m}$	Curie Temperature ^{o}C	Longitudinal Wave Velocity m/sec	Acoustic Impedance $(10^6)\ \frac{kg}{m^3} \cdot \frac{m}{s}$
Quartz	50	2	575	5750	15.2
PZT-4	24	255	340	4000	30.0
Barium Titanate	15	140	120	4460	24.0
Lithium Sulfate	175	16	75	5430	11.2

V/m - Volts per meter

N/m^2 - Newtons per square meter

m/m - meter per meter

m/sec - meter per second

kg/m^3 - kilograms per cubic meter

diameter. The natural resonant frequency in the thickness mode of vibration is approximately 160,000 hertz. The PZT-4 was chosen because of its ability to withstand heat, operate at high power levels if needed, and high efficiency as a driver and receiver. Characteristics of PZT-4 and other transducer materials are given in Table III. These discs were used in all of the transducers developed for this project.

The velocity of ultrasonic waves in good quality, dense concrete is on the order of 15,000 feet per second. Actually it can range from about 12,000 to 20,000 feet per second in good concrete. The higher values generally represent concrete of better quality.

Given an eight inch thick slab, a transmitted pulse could be reflected back to the front surface in 89 microseconds, assuming a 15,000 feet per second wave velocity. In order to minimize scattering, it was earlier said to be desirable to work at as low a frequency as possible (longer wavelength). Early experiments using a frequency of 160,000 hertz revealed a very severe scattering problem. If the transducer could be made to operate at 80,000 hertz, the scattering should be greatly reduced. At 80,000 hertz, each cycle takes 12.5 microseconds. Using a single transducer as both receiver and transmitter, a train of more than seven cycles would completely obscure the returning echo. A wave train one half this length would be more desirable. Transducer ringing would make it difficult to produce so short a pulse. In addition, overload recovery problems in the receiver amplifier would arise. These problems are reduced by using separate transducers for transmitting and receiving. Separation of the transducers increase the travel time for the reflected wave.

It is simpler to generate a short electrical pulse (a square or nearly square topped wave of very short duration) than a train of three to seven cycles of a sine wave at a given frequency. The transducer's ability to reproduce either the pulse or short wave train exactly is a function of its quality or Q. Q is defined as the device's natural resonant frequency divided by its bandwidth or range of frequencies over which it may operate. A Fourier Series analysis of either signal will show that it is made up of a fundamental frequency and an infinite number of harmonics. Amplitude decreases for the higher harmonics, but a wide range of frequency is needed if the signal is to be reproduced accurately. A short pulse requires a wider bandwidth and consequently lower Q to reproduce than a long pulse needs. The transducer will respond to the electrical pulse by producing a mechanical pulse with energy centered at its resonant frequency. The number of cycles of such oscillations (ringing) the transducer produces is a function of Q and damping (viscous friction). The resulting loss of efficiency may be compensated by choosing highly efficient, active components, such as PZT-4, and designing for maximum power transfer.

The early transducers were constructed as simply as possible in order to determine characteristics of the PZT-4, and to determine any general trend in the transducer's operation. A simple clamping device provided electrical contact on each side of the discs in order to apply the electrical pulse and to pick up the received signals. This transducer design made no provision for damping or impedance matching. Waves were radiated equally well in both directions. The transducers operated at their natural resonant frequency and the Q for the system was high. Ringing persisted for five to six hundred microseconds. Little longitudinal wave energy was transmitted into the concrete, even with a liquid interface. A strong Rayleigh surface wave signal was transmitted radially outward. The strong surface wave in the presence of a weak longitudinal wave revealed a high degree of mode conversion, scattering, or both.

A series of experiments were performed in an attempt to eliminate the large Rayleigh wave component. Hopefully then, any reflected longitudinal wave could be observed. Some literature indicates a reduction in Rayleigh surface waves with intermediate coupling layers such as Lucite or hard rubber, which do not carry shear waves well. Several of these materials were tried in varying thicknesses with no noticeable success.

An investigation of literature on sonar (sonic navigation and ranging) revealed that much research has been done in the field of piezoelectric transducer design for use in water. Such literature suggested using the active element as a quarter-wavelength resonator, with a quarter-wave backing plate resonator. The normal mode of operation is for the transducers to operate as half-wavelength resonators. Additional matching sections may be added on both sides in order to match impedances and provide damping. In essence, the complete transducer has become a mechanical transmission line and as such may be studied by equations associated with electrical transmission lines.

By neglecting any attenuation losses in the media, the acoustic impedance Z_i, looking into any length of medium 1 backed by medium 2, is calculated by the following equation:

$$Z_i = Z_1 \frac{Z_2 \cos \frac{2\pi L}{\lambda} + j \; Z_1 \sin \frac{2\pi L}{\lambda}}{Z_1 \cos \frac{2\pi L}{\lambda} + j \; Z_2 \sin \frac{2\pi L}{\lambda}}$$

where:

Z_1 - Acoustic impedance of medium 1.

Z_2 - Acoustic impedance of medium 2.

L - Length of medium 1.

λ - Wavelength in medium 1.

j - $\sqrt{-1}$

This is the impedance value to be used for reflection and transmission coefficient calculations.

It was previously stated that thin sections may be ignored for reflection calculations. In the above equation, if $L \ll \lambda$, then $\cos \frac{2\pi L}{\lambda}$ approaches unity and $\sin \frac{2\pi L}{\lambda}$ approaches zero. Then $Z_i = \frac{Z_1 Z_2}{Z_1} = Z_2$.

To show that a one-half wavelength section can be the most efficient coupling device, set $L = \lambda/2$.

Then:

$$Z_i = Z_1 \frac{Z_2 \cos \pi + j \; Z_1 \sin \pi}{Z_1 \cos \pi + j \; Z_2 \sin \pi} = Z_2$$

Note that the apparent acoustic impedance of the half-wavelength section is that of the load, its own impedance not being important for reflection and transmission coefficient calculations. The same conditions exist for multiples of a half-wavelength such as one wavelength, one and one-half wavelengths, etc. The shortest sections will have the lowest attenuation losses.

When it is desired to match two unequal impedances, a quarter-wavelength section is used as a transformer. Substituting $\lambda/4$ for L, the equation is now written:

$$Z_i = Z_1 \frac{Z_2 \cos \pi/2 + j\, Z_1 \sin \pi/2}{Z_1 \cos \pi/2 + j\, Z_2 \sin \pi/2}$$

or

$$Z_i = Z_1^2/Z_2$$

Solving for Z_1, the quarter-wavelength transformer's acoustic impedance, Z_1, should equal $\sqrt{Z_i Z_2}$, or in other words, the square root of the product of the two impedances to be coupled. This same section, may at the same time serve as a quarter-wavelength resonator.

The new transducer system design now began to evolve as an active quarter-wave resonator (PZT-4 discs) acting on a quarter-wavelength resonator transformer to couple it into the concrete. The back surface of the active resonator was loaded with another quarter-wavelength resonator of approximately the same acoustic impedance. Another would transform or match this impedance into a surrounding insulating and cooling medium.

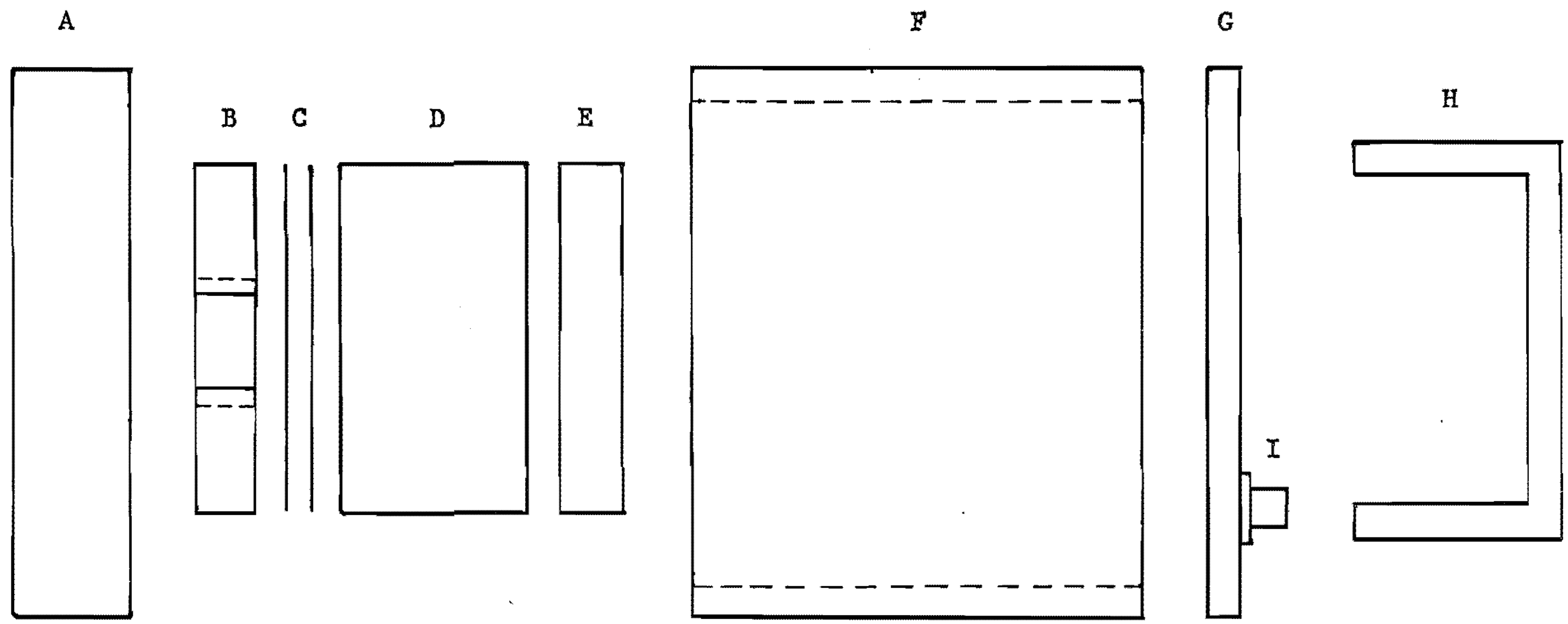
The acoustic impedance of the PZT-4 is 6.23×10^6 lb/ft^2-sec and that of the concrete approximately 2.25×10^6 lb/ft^2-sec. Concrete's acoustic impedance actually will vary widely. The matching section's impedance, Z_1, is set equal to the square root of the product of the acoustic impedances of concrete and PZT-4. This comes out to 3.74 X 10^6 lb/ft^2-sec. Table II shows that the acoustic impedance of aluminum as 3.54 X 10^6 lb/ft^2-sec, a very good approximation.

A steel resonator was used as a backing element. With an impedance of 9.57 X 10^6 lb/ft^2-sec it represented about a 50% mismatch. Copper would have been a better choice. The steel was chosen because it was on hand in the machine shop. Actually, a better choice, not realized at that time, would have been materials with much higher absorption rates.

Castor oil was chosen to use as a surrounding insulator and coolant. It would also provide wetting between the surfaces of the parts and provide damping due to its high viscosity. Acoustic impedance of castor oil is 0.29 X 10^6 lb/ft^2-sec.

Calculation of a series of two quarter-wavelength transmission lines to couple the PZT-4 and the castor oil may be simplified to $Z_{PZT} = Z_{CO}\left(\frac{Z_1}{Z_2}\right)^2$ where Z_1 is the acoustic impedance of the steel resonator. Solving for Z_2 gives a desired acoustic impedance of 2.08 X 10^6 lb/ft^2-sec. No material was found in tables with this impedance. Either aluminum ($Z = 3.54 \times 10^6$) or Lucite ($Z = 0.65 \times 10^6$) are fair approximations. Lucite was chosen because of a much higher attenuation than aluminum.

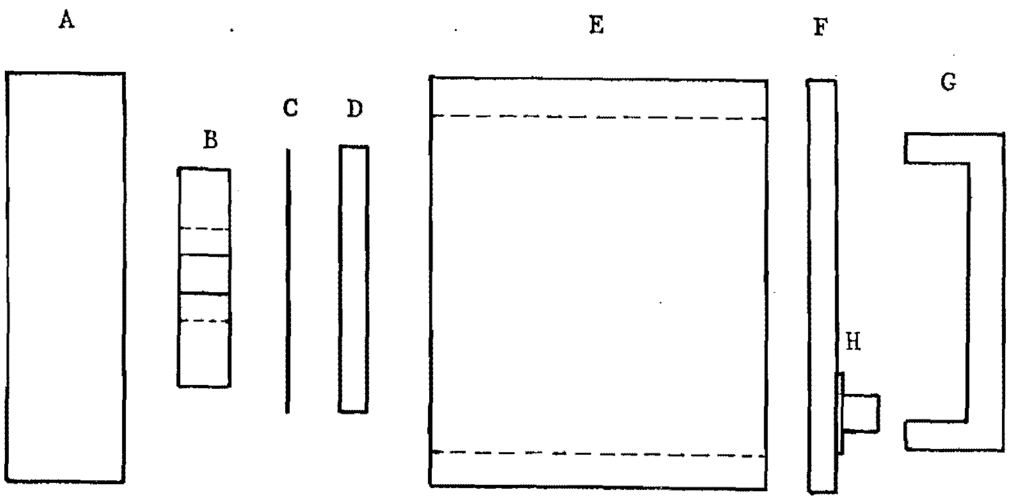
Transducer II was constructed as shown in Figure VI. Despite the severe acoustic impedance mismatch and low attenuation of the backing plates, the transducer worked very well. The resonant frequency was



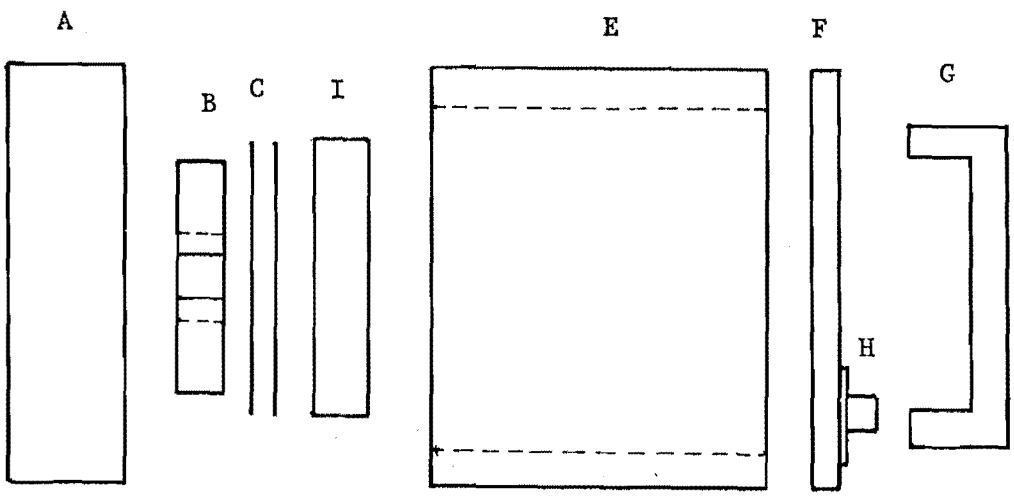
A - Quarter Wave Aluminum Faceplate
B - Three each PZT-4 Piezoelectric Discs
C - Electrical Contact & Insulator
D - Quarter Wave Steel Resonator
E - Quarter Wave Lucite Matching Plate

F - Housing
G - Top Cover Plate
H - Handle
I - Coaxial Cable Connector

Figure VI. Transducer II. Voids Filled with Castor Oil.



Receiving Transducer



Sending Transducer

A - Quarter Wave Aluminum Face Plate
B - Three each PZT-4 Discs
C - Electrical Contact
D - Lucite Holding Plate
E - Housing
F - Top Cover Plate
G - Handle
H - Coaxial Cable Connector
I - Quarter Wave Steel Resonator

Figure VII. Transducer III.
Receiving and Sending Units. Voids Filled with
Rubber Like Polymer and Lead Oxide Dust.

measured as 83,000 hertz. Ringing time was reduced to just under two hundred microseconds. Removal of the castor oil increased the time to about four hundred microseconds.

Using two of these transducers, longitudinal waves could be transmitted, although no direct reflections were observed. This received signal was weak while the Rayleigh waves were still strong. Again attempts to reduce the Rayleigh waves by the use of plastic and hard rubber intermediate layers proved unsuccessful. This indicates that the Rayleigh waves are the direct result of mode conversion at the concrete interface or within the concrete.

Realizing that these transducers needed improvement in design, one unit was rebuilt with no backing plate other than a thin Lucite holding clamp on the PZT-4 discs. The area around and above the PZT-4 discs and clamp was filled with a mixture of a rubber like polymer and lead oxide which had passed a 200 mesh sieve. The intention was for the transducer to resonate at 160,000 hertz, which would help it to have a linear response as a receiver for waves below this frequency. The fact that the front quarter-wavelength matching plate was also a resonator was overlooked until the frequency was later found to have remained at about 83,000 hertz. The sensitivity seemed higher than before, probably as a result of somewhat less damping.

The sending transducer was assembled in much the same way except the steel disc was left in and the Lucite omitted. The polymer-lead oxide combination was used to fill the voids around the elements. Ringing time dropped to about one hundred and twenty microseconds with a resonant frequency of 83,000 hertz. Figure VII shows these two transducers.

These two transducers were used to reflect a longitudinal wave off the bottom of a five inch slab as later described in the paragraph on results.

In an effort to increase the strength of the received longitudinal wave, aiming of the transducers was attempted. Lucite wedges were cut at various angles and held to both the transmitter and receiver. The first pair produced almost no longitudinal wave signals. The critical angle for Lucite to concrete was calculated (25°) and found to have been exceeded. Another pair of wedges were cut very close to the critical angle. Although more longitudinal waves now were received, they were less than when no wedges of any angle were used.

It was decided not to cut another set of Lucite wedges for a still smaller angle of incidence. Instead, aluminum wedges were designed to replace the quarter-wavelength faceplates on the transducers. The quarter-wavelength distance was kept in the centerline of the wedge in order to continue to provide some impedance matching. Aluminum wedges, having a higher wave velocity than concrete, also eliminate the critical angle problem. These wedges have been built but as yet are not installed and tested.

In order to use a single transducer system, the ringing time must be greatly decreased from the values achieved to date. An attempt was made to do this by using lead, quarter-wavelength resonators to replace the steel resonator. The high absorption of lead should help dampen out the PZT-4 ringing. One unit was modified and the resonant frequency went to about 250,000 hertz, too high a value to use. Since this is a higher frequency than that of the PZT-4 alone, it may be that some spurious mode of oscillation was induced. Investigation to determine just what happened has not yet been undertaken.

Another generation of transducers should be built, using better backing plate materials. It may then be found that the ringing time is short enough to proceed with development of a single transducer system.

DISCUSSION

The current method of measuring the depth of newly constructed pavement is to take a core sample and measure its length at three evenly spaced points around the circumference. Not only is this procedure expensive and time consuming, but it damages the pavement.

There are at least two nondestructive methods of measuring thickness of a slab using sonic or ultrasonic waves. One is to find the resonant frequency of the slab as a half-wave resonator, measure the wave velocity in the slab, then calculate:

$$t = v/2f$$

t - Thickness

v - Velocity

f - Resonant frequency

This system was demonstrated by Mr. Richard Muenow of the Portland Cement Association in 1963. Two separate measurements are required in order to calculate the thickness.

It was felt that a system using ultrasonic ranging could be built. Its operation is like that of radar, except that ultrasonic mechanical waves, not electromagnetic waves, are sent outward. A receiver picks up the echoes returning from the pavement-base interface and displays them on an oscilloscope screen.

Having chosen to use piezoelectric transducers as explained in a previous section, an initial series of experiments were run to determine piezoelectric transducer characteristics.

The first transducers produced nothing more than Rayleigh surface waves. Re-design progressively improved transducer operation until it was possible to receive waves reflected off the bottom of the slab.

A single transducer system is one in which the same transducer is both sender and receiver. In this system, the reflected wave has the shortest distance to travel before being received. The return signal will be stronger than in two transducer systems but the wave's transit time will be shorter. None of the transducers developed in this project were suitable for single transducer operation due to the ringing times being too long.

Because of this lengthy ringing time, a two transducer system was adopted where separate transducers function as sender and receiver. But now the Rayleigh surface wave from the sender, having a shorter distance to travel to the receiver than the reflected wave, completely obscured the weak reflected wave. No way was found to halt the generation of Rayleigh waves, but it was found that they traveled at about one half the speed of the longitudinal wave. The obvious solution was to separate the two transducers enough so that the slower Rayleigh wave reached the transducer later than the reflected longitudinal wave. The path, P, the longitudinal wave travels may be calculated as follows:

$$P = \sqrt{4t^2 + S^2}$$

where

t - Pavement thickness

S - Transducer spacing

A major disadvantage of the two transducer system is that this longer travel path attenuates the amplitude of the received wave. Increase in transmitter power output and transducer efficiencies may eliminate this problem. Further experiments in improving the transducers, have not made any material improvements in their effectiveness. It is felt, however, that much can be done along this line.

RESULTS

This research program did not achieve its final goal of developing a nondestructive test for measurement of concrete pavement thickness; however, considerable progress was made. Signals reflected from the bottom of a five inch slab were received. These signals were received with transducer spacing distances varying from ten inches to 44 inches.

At distances beyond a 24 inch spacing, accuracy of measurement of the travel time became very poor due to the necessity to change time sweep ranges on the oscilloscope. Therefore, data recorded for signals beyond 24 inches is not shown on the graph in Figure VIII.

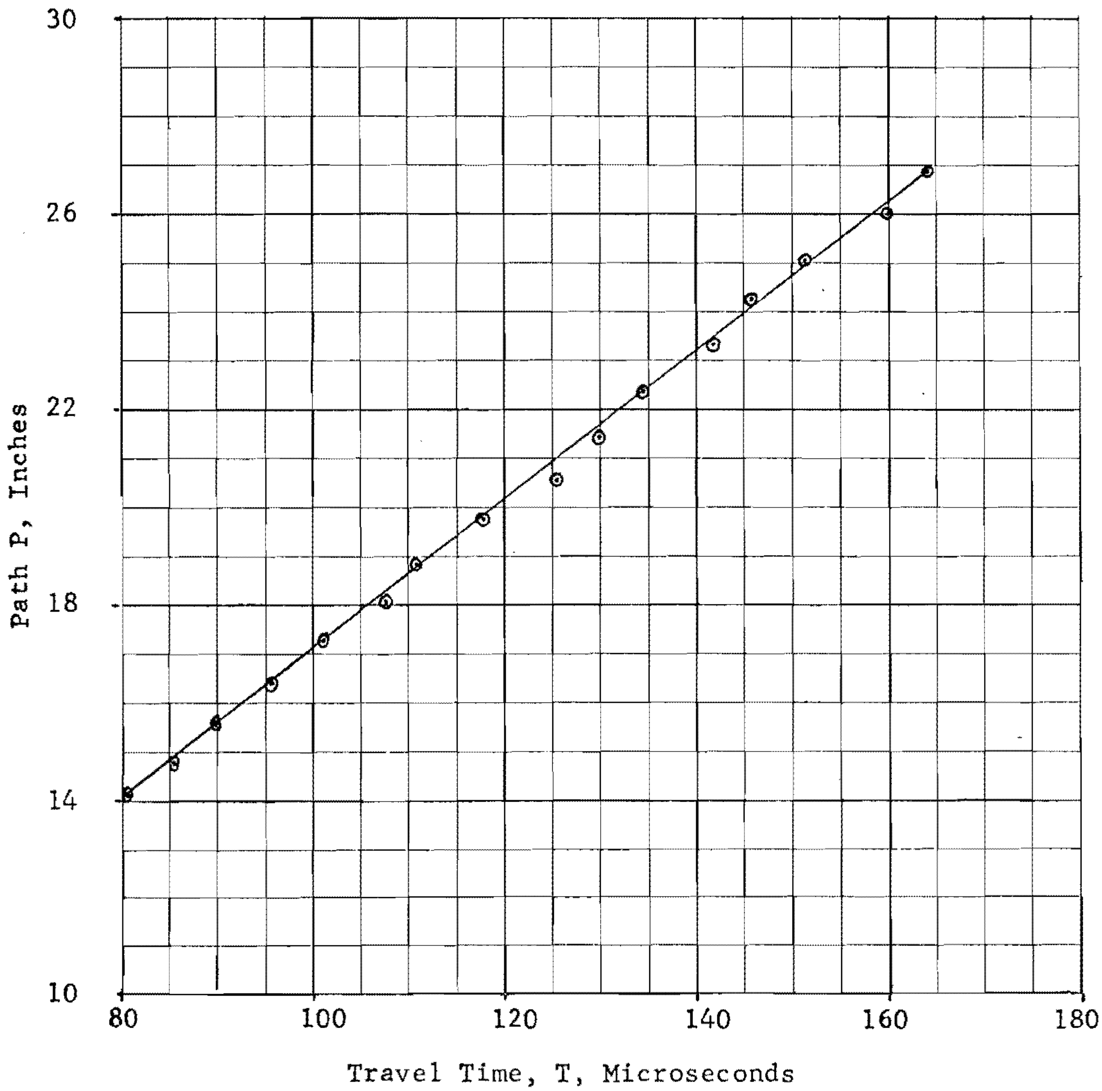


Figure VIII. Path, P, of Reflected Longitudinal Wave
vs.
Travel Time, T
$P = (0.154)\,T + 1.66$

This report has been prepared by the Principal Investigator and reviewed by the Project Supervisor.

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