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FOR
HYDROYIELD MEASUREMENTS

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INVESTIGATION OF OPTICAL METHODS
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HYDROYIELD MEASUREMENTS

FINAL REPORT

by J.A. CHAREST
&
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SUMMARY

Two fiber optic techniques, the Linear Resistive Ladder (LRL) and the piezo-driven LED arrangement, were investigated and successfully demonstrated in the laboratory to be capable of being used for hydroyield measurements. Prototype linear arrangements for each of the above methods were constructed and placed in a designated UGT. The piezo-driven LED method appears very attractive as it showed the potential for becoming an "all passive, non-intrusive" treaty verification method capable of functioning at stress levels ranging from less than 1Kbar to 100Kbars. Other optical methods using fiber optics for detection mechanisms and signal transmissions were also conceptually examined.

1. INTRODUCTION

Over the past few years, the need has arisen at the UC Lawrence Livermore National Laboratory to improve existing methods or develop new approaches for accurate hydroyield measurements of underground nuclear explosions. Currently, such measurements primarily rely upon the use of the so-called CORTEX cable and to a lesser degree on the Slifer. However, since both of the above techniques utilize an electrical cable for shock wave front detection, their measurement capability can be seriously impaired due to EMP pick-ups and their acceptance for treaty verification diminished for possibly being intrusive. The use of fiber optics for generating and transmitting to a distant recorder the information of hydroyield measurements has recently become a subject of investigation, as such an approach is believed capable of the above capabilities without being intrusive. Indeed, fiber optics are immune to EMP effects and can be made to be radiation insensitive when properly utilized.

Methods are examined here that utilize fiber optics for the generation and transmission of light signals from which hydroyield measurements can be made. Emphasis is given to those approaches that appear most promising using currently available information. Two specific arrangements are experimentally investigated along with their adaptations to the constructions of linear sensors that are to be used in dedicated UGT.

2. TECHNICAL CONSIDERATIONS

A brief review of technique considerations is provided here for the benefit

of the reader along with individual discussions of fiber optic techniques which can be used for verification hydroyield measurements. Detailed technical considerations on fiber optic functioning are not included here as they can be found elsewhere. Our discussions primarily focus on concepts and their potential applications, assuming that any techniques considered may produce light impulses that can be integrally transmitted via fiber optic lines and adequately detected.

2.1 Hydroyield Measurement: Concept and Definitions

A hydroyield measurement is specifically referred to in the context of this document as a time-resolved position measurement of a shock front that is imparted to the geology surrounding an underground nuclear explosion and its use to infer the yield of the working device. Two typical scenarios apply. See Figure 1. They are the on-axis (main-hole) and the off-axis (satellite hole) measurements. The on-axis measurement is, of course, a highly desirable approach as it does not require connections which otherwise are needed to account for the angle of attack upon the sensing element by the shock front. On the other hand, off-axis measurement, an approach that is possibly more acceptable for verification purposes, does require greater resolution capability than the on-axis method as greater apparent shock velocity detection is needed. Ideally, a verification method should be passive, non-intrusive, and capable of accurate shock velocity measurements in excess of 10.0 mm/ μ sec and one-microsecond time-resolutions. Such a method has yet to be developed using either optical or electrical techniques. The application of fiber optic techniques to verification technology appears to be promising.

Shock velocity measurements with fiber optics can be classified as 1) incremental or continuous, 2) passive or active, and 3) all optical and electro-optical. By incremental we mean an average shock velocity that is inferred from a shock transit time between two fixed positions. By passive we mean a technique that does not utilize an external energy source but solely depends on the shock wave interaction with the sensing element. By all-optical we mean a technique that does require or use electricity in the formation and transmission of the optical signal (except at the detector at the trailer). A few techniques that utilize fiber optics are examined next as they show potential applications toward future verification activities.

2.2 Fiber Optic Hydroyield Measurement Methods

Linear Resistive Crush Cable: Incremental, Active, Electro-optical

The linear resistive crush cable, also known as LRL (See Figure 2a), consists of discharging a series of short-duration electrical pulses into an LED (light emitting diode) and in creating light signals that depict the position in time of a shock front. The source of the electrical pulses is simply the output of a wheatstone bridge arrangement that is completed externally by a linear arrangement consisting of several discrete resistors connected in series (i.e., the crush cable arrangement). As the shock front travels along the cable, a short circuit is created thus causing the resistance of the linear arrangement to decrease and to produce a stair-case output signal such as the one shown in Figure 2b.

Differentiation of the above signal therefore produces a series of short-duration impulses which in turn are used to drive the LED and ultimately generate the desired optical pulses. See Figure 2c.

The main attributes of the linear resistive crush cable are its already proven working concept and the fact that its output can be precisely bench-marked and amplitude controlled to improve confidence in the data. The output of the linear resistive arrangement is typically incremental although short distances between resistors can be made small, thus rendering the technique semi-continuous. This method requires electrical power in the down-hole. Such power can be provided by a battery pack arrangement which can be remotely turned on using an optical signal from a distant trailer. The linear resistive concept is believed to be applicable to stresses ranging from a few bars to hundreds of Kbars. Construction of actual linear arrangements are considered straight forward. Adequate shielding techniques against EMP and radiation effects remain to be investigated.

Techniques that utilize discrete self-shortening pins instead of a continuous linear resistor can also be developed which would emulate the crush resistive cable. Their implementations into actual linear sensors is thought to be bulky and awkward as they require one electrical cable per shortening pin.

Piezo-Assisted LED Arrangement: Incremental, Passive, Electro-Optical

The piezo-assisted LED impulse method consists of a direct discharge

of a piezoelectric probe's output into an LED and in the creation of a series of light impulses that depict the position of a shock wave front moving along a linear sensing arrangement. Two construction concepts are possible: They are the Multi Piezo Probe Concept with a single LED, known as the PET arrangement, and the Multi Piezo Probe/LED Concept, known as the POP arrangement. See Figure 3. The PET arrangement requires the use of relatively long individual electrical cables for each piezo sensor but only one LED. The POP system requires several units of piezo sensors/LED arrangements using only short links of electrical connections. Although more complex to construct, the POP arrangement appears to be less sensitive to EMP effects than the PET system. Its practical implementation into linear sensing systems and its functionality remain to be established. Both the PET and the POP techniques are incremental and passive in nature and in principle do not require an external source of power for their functioning. Both techniques offer the potential for producing optical signals that are sufficiently strong for unassisted transmission to a distant recorder via fiber optic.* Their assembling into practical arrangements can be arrived at from off-the-shelf commercial components.

*A light detector and repeater (LDR) is not needed in the down-hole.

Shock-Induced Luminescence: Incremental, Passive, All Optical

Shock-induced luminescence means the production of a light impulse when a substance is rapidly compressed by the action of a shock wave. The application of this phenomenon toward shock wave metrology has already been done for over several decades using noble gases. Shock induced luminescence in fluids and solids is still a field of endeavor that remains to be investigated for future applications toward shock wave measurements. The concept of several light producing cavities that make use of noble gases and a single optical fiber is a very appealing idea as it has the potential for being converted to an all optical passive verification method that is immune to EMP and radiation effects. See Figure 4 for concepts of techniques. Whether or not such techniques are feasible remains to be investigated.

Shock-Induced Reflection: Incremental/Continuous, Active, All-Optical

The use of light reflection from a moving surface (time domain reflectometry or the Doppler Shift) to infer its displacement is an approach that has already received numerous applications in the laboratory. Its incorporation into a verification scheme is very appealing

as it could ultimately result in the development of non-intrusive all-optical continuous measurement methods (i.e., the velocity interferometer or light ranging and detecting via amplitude modulation). Whether or not sufficient light reflection can be produced at a shock-induced crush point of an optical fiber or a small light pipe is the key fundamental question that remains to be answered. There is a minimum 4% reflection of light at the exit of a fiber due to refractive index differences. See Figure 5 for technique concepts that utilize light reflection to infer the displacement of a moving surface.

A fiber optic VISAR system will require the use of expensive single mode fibers to eliminate modal dispersion. The light ranging and detection scheme can be used with less expensive multi-mode fibers.

3. EXPERIMENTAL INVESTIGATIONS OF TECHNIQUES

In this study we are investigating two linear shock-front detecting concepts in preparation for a dedicated UGT event. They are the crush or LRL cable and the piezo-assisted LED or PET arrangement.

3.1 Linear Resistive Crush Cable (LRL)

Our current approach to a linear resistive crush cable arrangement centers on the use of an already-existing and-proven technology. It basically consists in modifying the well known 50 Ω piezoresistive pulse power supply arrangement (Figure 6A) toward meeting four specific requirements and in designing a rugged linear resistive cable that is suitable for field applications. The four specific requirements of the power supply are as follows:

- 1) Choice of charge capacitor and working voltage for field work.
- 2) Design a bridge output differentiation and an LED driver.
- 3) Design a self-triggering mechanism that relies upon cable crush.
- 4) Test of the power supply arrangement using fiber optic links.

The design of the crush cable centered around a design concept that could be easily assembled into a sturdy unit from simple parts and existing hardware. See Figure 7.

Pulse Power Supply: Bridge Circuitry and LED Driver

Figure 6 shows the basic circuitry arrived at in this work to meet the above requirements. The design centered around the use of a fixed charge

voltage of 47 volts and a 17,000 μ f charge capacitor. A differentiator/line-driver arrangement was formulated to accept and differentiate the bridge output and be capable of driving the LED unit to be provided by LLNL. An actual circuit of the above arrangement was constructed on a dedicated PC board and bench tested. That same circuit board was to be used later on for a dedicated UGT.

Gas Gun Testing of Linear Resistive Crush Cable

Several gas gun tests were conducted on short links (six 0.5Ω discrete resistors) of prototype linear resistive arrangements to determine the viability of the concept as well as to implement corrections on the system to be exercised in an assigned UGT. Figure 8 shows the basic test arrangement and the output generated by the bridge/differentiator/linear driver arrangement of Figure 6b. As one can see the test was designed to create a series of pulses that were separated in time by approximately 5 microseconds. Aside from a short-duration turn-on transient, the output of the system appears to be well within the intended capability of its design, and thus suitable for UGT applications.

3.2 Piezo-Assisted LED

Our approach to the piezo-assisted LED concept centered on the use of commercially available piezoelectric probes commonly called pins and a linear construction arrangement that depicts Figure 3a. Such a construction is basically straight forward and is very attractive due to the fact that the concept of a piezo driven LED had already been reported to work. The main goal of this investigation was therefore directed at measuring the charge output versus impact stress of the piezoelectric device (Dynasen's CA-1136 piezo pin: .093" diameter) chosen for this work.

Gas Gun Testing of Piezoelectric Devices (Pins)

Figure 9 shows the basic test arrangement used to derive the output charge release versus stress of the piezo-pin mode, Dynasen Part #CA-1136. Figure 10 is a set of representative output data (electrical and optical) for an arrangement, the PET arrangement that was to be used in an upcoming UGT. Figure 11 is the charge released by the piezo-pins versus stress as it was measured using the scheme of Figure 9b2. As one can see, it appears that the charge released by a piezo pin device remains nearly constant over a wide range of stress ($1.0\text{Kbar} < \sigma < 100\text{Kbar}$) thus

rendering it very attractive for UGT applications. Indeed, the very fact that a constant charge output can be generated regardless of the pressure applied means that an accurate control in output can be achieved from a piezo driven instrument using piezoceramics.

4. CONCLUSIONS

The results of this investigation clearly show the potential of the linear resistive concept (LRL) and the piezo-driven LED (PET) approach toward verification instrumentation schemes. Further efforts should be directed toward optimizing both of the technique's circuitries and in establishing the operations requirements from further laboratory testing. Particular attention should be given to the PET technique and its miniaturization. Indeed, it shows great possibilities for verification applications. Of course, experimental investigations of the "POP" technique (piezo-ceramic/short link of cable and an LED) should also be addressed as it might be less sensitive to EMP effects.

Techniques that utilize a source of light (laser) at the recording trailer and depend upon reflection or doppler shift through an optical fiber should also be considered. These techniques have been shown theoretically to be capable of high resolution continuous measurement of shock position vs. time. Both a fiber optic VISAR system and an amplitude modulated light "radar" system have been designed.

Figure 1. Hydroyield Measurement Schemes

- A -

- B -

- C -

Figure 2. Linear Resistive Crush Cable - Discrete Resistor

- A -

- B -

Figure 3. Piezo Assisted LED Arrangements

FIGURE 4. Shock Induced Luminescence Arrangements

FIGURE 5. Shock Induced Reflection

FIGURE 7: DESIGN OF LINEAR RESISTOR CABLE (LRL)

-A- Test Arrangement

-B- Output of Bridge/Differentiator/Line Driver

Figure 8. Test Arrangement and Output of Linear Resistive Cable

-A- Impact Test Arrangement

-B- Recording Arrangement

Figure 9. Testing of Piezoelectric Pins

-A- Electrical Output
at 50Ω

Time 5μsce/Div.

-B- Output of Optical
Receiver

Time 5μsec/Div.

Figure 10. Representative Output of the PET Technique Using
Piezo Pins

0.020" THICK X 0.052" DIAMETER PZT 5A
PIEZO CERAMIC CRYSTAL

Figure 11. Release of Electrical Charge by PZT 5A Piezoceramic

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