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ULTRASONIC MEASUREMENTS OF BORE TEMPERATURE IN LARGE CALIBER GUNS

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ABSTRACT. The Navy has a need to measure temperatures at critical areas on large caliber gun inner bore surfaces to insure appropriate action is taken in case of a misfire. Inappropriate actions could result in the loss of life and the disabling of a naval warship. In this report we describe the development of an ultrasonic-based sensor capable of non-intrusively measuring internal bore temperature. The results obtained during live fire field trials will be presented.

Keywords: Cook-off, Auto-ignition, Heat flux, Ultrasonic, Gun barrel, Temperature, non-intrusive
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INTRODUCTION

Two serious safety concerns when firing large caliber guns are propellant and explosive cook-off. Cook-off, also known as auto-ignition, can occur when enough heat from the hot barrel enters a chambered round, causing the premature, unintended, ignition of either the propellant or the explosive. The likelihood of initiating cook-off increases when the round remains in the hot barrel for an extended time period, such as might occur during misfire. In order for the crew to safely handle the misfire event, they must have an adequate amount of time to either take corrective actions or to evacuate the area in the vicinity of the weapon. Inappropriate actions could result in the loss of life and the disablement of a naval warship. There is currently no means of non-intrusively measuring the internal temperature during a live firing regiment.

Ultrasound has the potential to non-intrusively measure internal bore temperature. The use of ultrasound to measure average temperature within a structure is not new. Techniques suitable for measurements in solids, liquids, and gases have been reported to be available for more than 50 years [1]. Ultrasonic-based measurement techniques with sub-millisecond temporal response and with the capability of measuring temperatures as high as 9000 degrees K in shock tubes [2] and greater than 20,000 degrees K in plasmas [3] have been demonstrated. Thin wire sensors have been used in nuclear and industrial applications where conditions preclude the use of thermocouples, resistance devices or optical pyrometers [4].

In this article we exploit the unique structure of the rifled region of a gun barrel to measure internal temperature. The temperature localization relies on the echo “doublet” found in the rifled region. For the smooth bore region, determination of internal surface temperature and heat flux using a single interface echo in combination with inverse methods has been described elsewhere[5,6].

THEORY

Variation of Time-of-Flight with Temperature

The temperature estimation method is based on the thermal dependence of the ultrasound echo that accounts for two different physical phenomena: local change in speed of sound due to changes in temperature and thermal expansion of the propagating medium. The former produces an apparent shift in the scattering interface location, and the latter leads to a physical shift. The two effects lead to echo time shifts that can be estimated and are shown to be related to the local change in temperature within the propagating medium [7]. The basic equation relating the time-of-flight, G(x), to material dimensions and properties is given in Equation 1. This includes both thermal expansion and temperature-dependent velocity.

$$G(x) = 2\int_0^x \frac{1+\alpha(\xi)\delta\theta(\xi)}{c(\xi,\theta(\xi))} d\xi \tag{1}$$

The temperature in the propagating medium is assumed to be constant and equal to θ_0 at the initial time t_0. We start by considering the time delay of the echo from an echo at axial depth x. Here $\theta(\xi) = \theta_0 + \delta\theta(\xi)$ is the temperature at depth, ξ , $c(\xi, \theta(\xi))$ represents the speed of sound at depth ξ and temperature $\theta(\xi)$, and $\alpha(\xi)$ is the linear coefficient of thermal expansion of the medium at axial depth ξ .

At the initial time, $t_0 = 0$, the echo time delay is $G_0(x) = 2\int_0^x \frac{1}{c(\xi,\theta_0)} d\xi$. Once the temperature in the material changes, a variation in the time-of-flight (TOF) will be observed on the echo from an interface at axial distance x,

$$\delta G(x) = G(x) - G_0(x) \ . \tag{2}$$

By defining the ultrasonic velocity coefficient, β, the speed of sound is

$$c(x, \theta(x)) = c_0(x)(1 - \beta(x)\delta\theta(x)) \tag{3}$$

and the combined ultrasonic velocity-thermal expansion coefficient, P_{pm}, is

$$P_{pm}(x) = \alpha(x) + \beta(x) \ . \tag{4}$$

For reflecting interfaces located at x and x + Δx, the temperature change, δθ(x), is given by

$$\delta\theta(x) = \frac{c_0(x)}{2\Delta x}\left(\frac{1}{P_{pm}(x)}\right)\cdot(\delta G(x)) = \left(\frac{1}{P_{pm}(x)}\right)\left(\frac{\delta G(x)}{G_o}\right) \ . \tag{5}$$

With this initialization, the local temperature variation between two reflecting interfaces depends only on a single material parameter, the velocity-expansion coefficient, P_{pm}, and the fractional change in ultrasonic time-of-flight. Furthermore, this local temperature is independent of the temperature of the intervening medium. Measurements can be made even when the physical spacing between the echo pair, Δx is not known. This result only requires that the material properties are uniform in the region between x and x + Δx and that enough time has elapsed for this region, Δx, to be considered isothermal. For this application the gauge variation in the gun barrel rifled region gives rise to a pair of echoes that can be used to estimate internal barrel temperature.

EXPERIMENTAL

Rifled Region Echoes

Initial experiments were carried out in the laboratory on a relatively small section of a MK 45 MOD 4 gun. This work focused on two primary areas 1) propagation studies in the rifled region of the gun and 2) measurement of velocity-expansion coefficient. For the MK45 MOD 4 gun the barrel wall thickness in the region of interest was in excess of 2.5 inches. A portion of the inner barrel wall was smooth while other areas of the barrel contained the rifled region. The rifling is used to impart a spin on the projectile for stabilization. The rifled region consists of a periodic change in gauge thickness which is arranged around the circumference of the barrel. The "step" height is on the order of 0.050" with a period (in circumferential direction) of ~0.30". The rifling has a ~5 degree spiral down the length of the barrel.

The gun barrel material is a fine-grained steel with excellent ultrasonic propagation characteristics such that very high frequency ultrasound (>30 MHz) could be used. Using an ultrasonic transducer mounted on the exterior surface as indicated in Figure 1a, one can produce an echo "doublet" as shown in Figure 1b. The round trip TOF is approximately 25.5 microseconds. The first echo in Figure 1b arises from one of the rifling depressions (grooves), while the second echo is from one of the rifling raised areas (lands). The separation between these two echoes is approximately 440 nanoseconds. These results demonstrate the excellent propagation characteristics of the gun barrel materials and the exceptional separation of the echoes from the rifled region.

Material Properties

In order to convert the measured time-of-flight (TOF) to a local temperature it is necessary to measure the temperature dependence of the ultrasonic velocity-expansion coefficient, P_{pm}, of the material in the rifled region. Even though the rifled region material is treated with a thin, erosion resistant layer, it is reasonable to assume that its P_{pm} value will be similar to that of the gun barrel steel. Figure 1c shows the measured velocity as a function of temperature obtained on a 2 inch long segment taken from a gun barrel. These data were obtained by slowly heating the entire sample using a step-wise heating profile while independently monitoring the temperature with a thermocouple. For these data, the sample thickness was measured at ambient temperature and no correction for thermal expansion was applied. Thus, the resulting curve includes both the effects of the velocity change as well as the thermal expansion. The velocity-expansion parameter, P_{pm}, is the slope of this curve and was found to be 125 ppm/ ^{o}C.

Laboratory Experiments

The rationale underpinning this work is that by monitoring the small variation in TOF of the rifled echoes one can measure the local temperature with a sensor attached to the external surface of a gun barrel. The block diagram description of the instrumentation used for both the laboratory measurements and field trials is shown in Figure 2. The measurement system consists of an embedded computer linked via PXI bus structure to an analog-to-digital converter, thermocouple signal conditioner, and ultrasonic pulser/receiver. A user interface and associated control software have been developed to facilitate laboratory studies. The accurate measurement of temperature using ultrasound requires precise timing measurements. In order to obtain sub-sampling timing precision it is necessary to measure TOF using cross-correlation and interpolation methods [8].

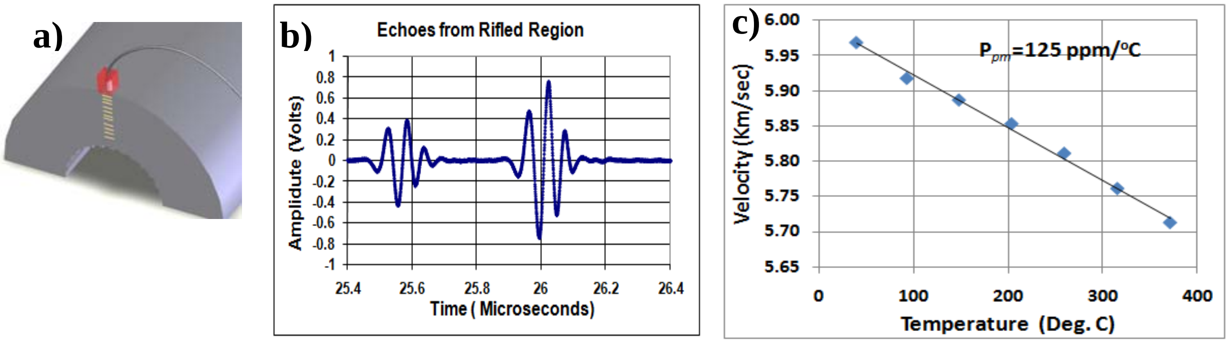

FIGURE 1. a) Gun barrel pulse-echo geometry; b) Echo pattern (doublet) from rifled region of a MK 45 MOD 4 gun; and c) Ultrasonic velocity versus temperature for gun barrel steel.

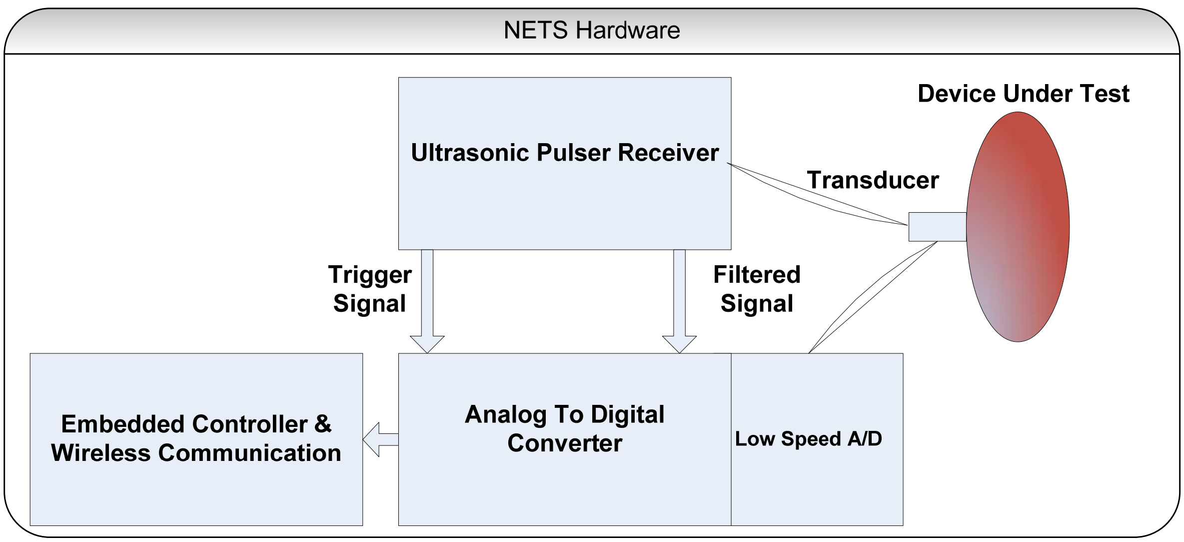

FIGURE 2. Overview of laboratory and field system showing all major components involved in the acquisition and processing of ultrasonic signals used in the determination of temperature.

To demonstrate the feasibility of the proposed temperature sensor a series of laboratory tests were conducted. Figure 3a shows a test configuration where a 0.050" step was machined into one end of a 2 inch long rectangular 316 stainless steel block. This is intended to replicate the situation encountered in the gun rifled section. The block was then instrumented with an ultrasonic sensor attached to the non-machined surface and two thermocouples on the exterior surface. One thermocouple, T1, was placed adjacent to the step, while the other thermocouple, T2, was placed on the sidewall of the test block. The bottom surface adjacent to the step was insulated while the sidewalls of the test block were surrounded by heating tapes. The echo pattern shown in Figure 1b is similar to that obtained from the step.

In Figure 3b we show the temperature and TOF data obtained while the block is heated using the sidewall heaters. The pair of echoes, an echo from each side of the step, is separated by approximately 440 nanoseconds. In Figure 3b we show both the temperature monitored at the middle of the block adjacent to the heaters (T2) and at the step (T1). In this example, we have used a 3-temperature stepwise heating pattern. In addition to the temperatures we have also plotted the measured echo pair transit time separation as a function of time. As can be seen from the data, the measured TOF closely parallels the thermocouple measurement at the step (T1) both on the heat-up and the cool-down. This confirms that the variation in TOF is related to the local temperature in the step region. These results also indicate that due to the small thickness of the step (~0.050”), the variations in TOF are quite small. In this case, a variation of 200°C produces less than 10 nanoseconds change in TOF. However, this is well within the measurement capability.

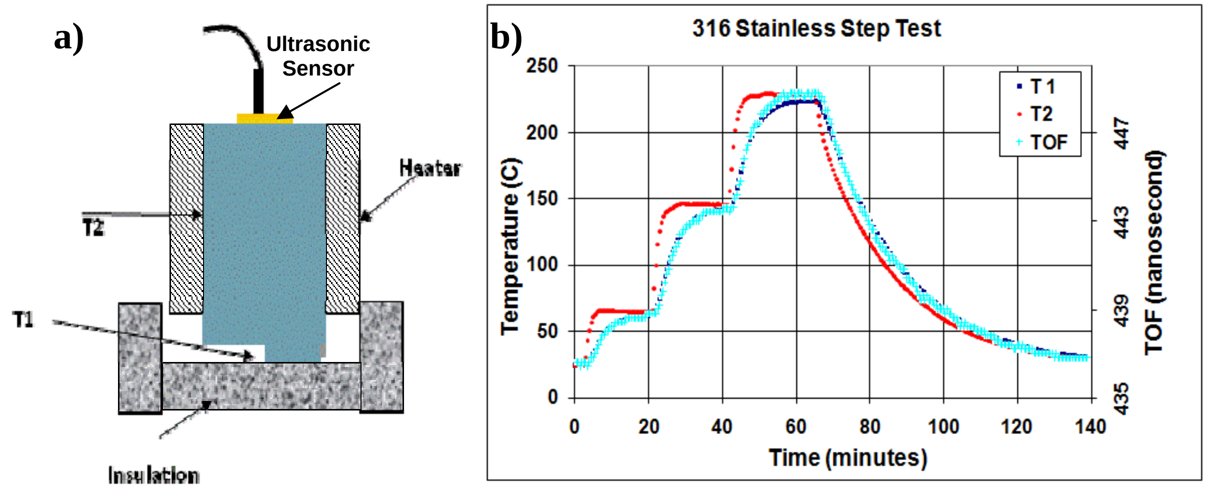

FIGURE 3. a) Test configuration for controlled “step” analysis; b) Thermocouple temperature measurements and ultrasonic time-of-flight (TOF) for echo “doublet” arising from the step. T1 is the “step” thermocouple; T2 is the sidewall thermocouple.

LIVE FIRE TRIALS

Laboratory studies demonstrate that there is sufficient signal-to-noise, bandwidth, and sensitivity to measure the required TOF changes in the gun rifled section. The next hurdle to be addressed is to demonstrate that the measurement methods are sufficiently robust to be applied to a gun under live fire conditions. A series of land-based live-fire trials were conducted using prototype sensors and instrumentation. The instrumentation was identical to that used for the laboratory studies. However, the sensors needed to be modified to accommodate the challenges posed by the live fire environment. Two different configurations have been evaluated: 1) sliding contact and 2) clamped element configuration.

The initial live fire trials were conducted at the Naval Surface Weapons Center Dahlgren Division (NSWCDD) using a sliding contact configuration on their MK 45 MOD 4 gun depicted in Figure 4. In the sliding contact configuration, the sensor is rigidly attached to the gun slide cylinder and is stationary during the firing. The sensor is coupled to the surface using a fluid couplant. For the large caliber guns considered for this application, the gun recoil is significant. The barrel translates several inches after each firing before returning to its initial position. Although TOF measurements on individual firing events showed some promise, multiple firings suggest that the sliding contact coupling exhibits too much variability for reliable temperature measurements.

A second coupling method, a clamping configuration, led to more reliable data. The clamping configuration involves bonding or mechanically attaching the sensor to the gun barrel so that it “rides along with” the recoiling barrel. In these experiments, the 10 MHz sensor is mechanically fixed to the external surface of the gun using an encircling strap.

Figure 5 shows typical high temporal resolution TOF data (200microseconds/point) obtained for three firings using the clamped sensor configuration. In order to compare the shape of the TOF data, the baseline was normalized to zero for each pre-fire condition. The first two rounds plotted in Figure 5 were MK 92 (blind loaded and plugged) warming rounds while the third round which shows a slightly different heating profile was a MK 160 (high explosive) round. The measured TOF profiles of rounds 1 and 2 are essentially identical. The higher energy round, #3, exhibits a larger initial TOF spike and higher TOF change at 6 seconds post firing.

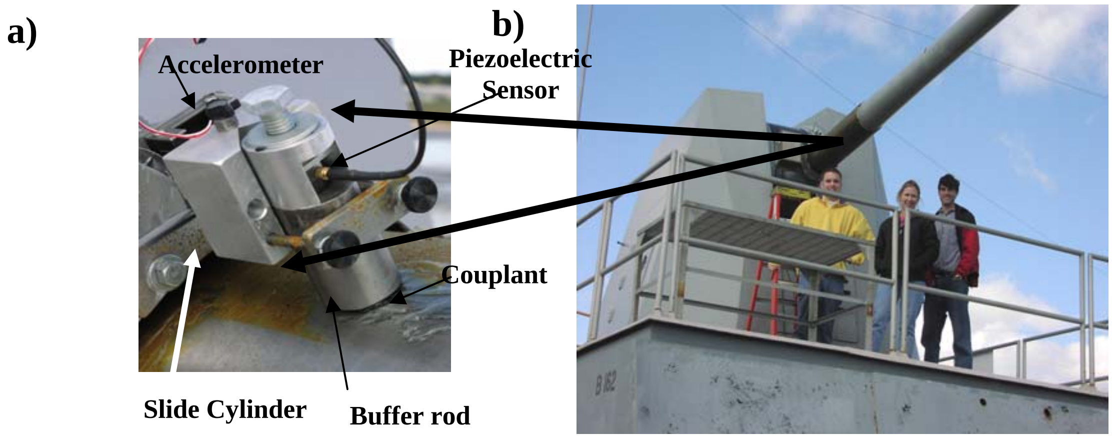

FIGURE 4 a) Sliding contact probe mounted to gun slide cylinder b) MK 45 MOD 4 gun at NSWCDD.

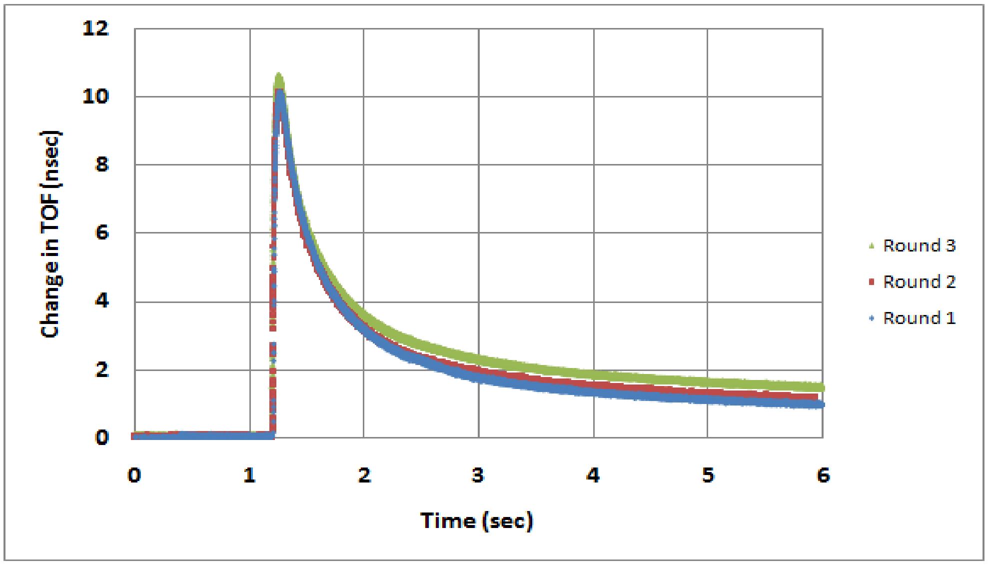

FIGURE 5. TOF measurements for 3 rounds using the clamped contact probe configuration. TOF measurements were made every 200 microseconds.

The clamped probe configuration proved to be highly stable and reliable. This method was used to acquire TOF data during an additional 64 round firing regiment. Figure 6 shows the "average" barrel temperature determined by monitoring the TOF variation for a single echo from the bore inner surface (through-the-wall) over 64 firing events. In this case we are measuring the TOF variation over the entire barrel thickness. Strictly speaking this only provides a "true" average temperature under nearly isothermal conditions. For this test, the time interval between the firing of successive rounds was generally more than 120 seconds. This is sufficient time for the barrel inner wall and barrel outer wall to equilibrate.

The velocity-expansion coefficient of 125 ppm/^{o}C was used to convert the TOF measurements to temperature. Figure 6 is presented primarily to illustrate the robustness of the clamping method in obtaining reliable temperature data. These data represent a full days firing regiment. Twenty rounds were fired prior to a lunch break. The barrel was air cooled during lunch. An additional 20 rounds were fired before the barrel was water-cooled and then a further 24 rounds fired to finish the test.

For a more rapid firing sequence it is necessary to combine the rifled region TOF data and the through-the-barrel wall TOF data. The through-the-barrel average temperature measurement is less sensitive to coupling variations and more accurate for longer-term variation (<60 seconds after firing). The rifled region measurements show rapid response and are best suited for determining rapid, local, variations with temperature. The combined data for four of the firing events shown in Figure 6 are presented in Figure 7. As can be seen in Figure 7, each firing event is accompanied by a very rapid rise in surface temperature followed by a slower decay to a baseline value. Each firing event gives rise to a "step" increase in the barrel temperature.

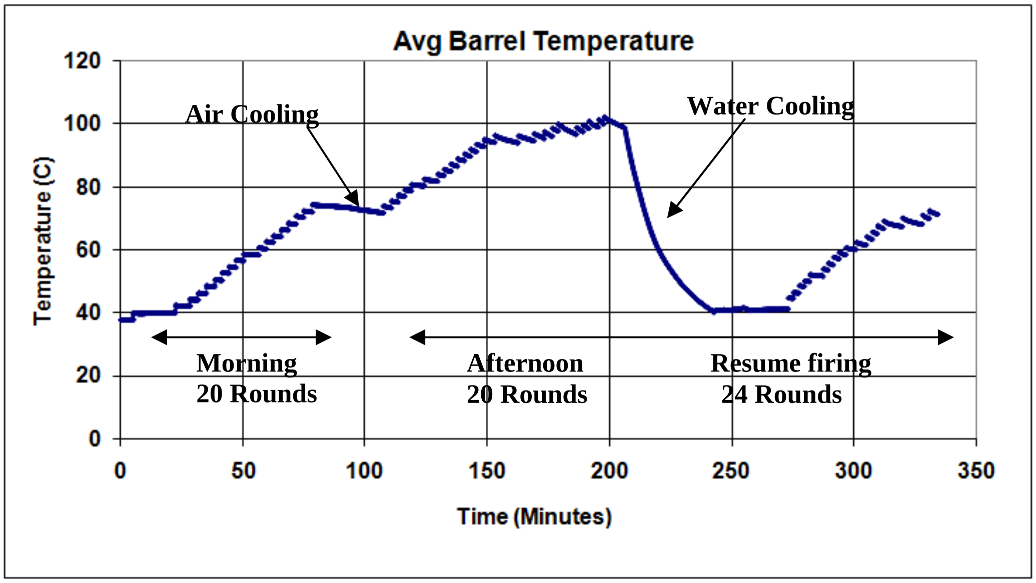

FIGURE 6. "Average" barrel temperature extracted from ultrasonic TOF data for a 64 round firing sequence of a MK45 MOD 4 gun. A velocity-expansion coefficient of 125 ppm/^{o}C was used to convert TOF data to temperature.

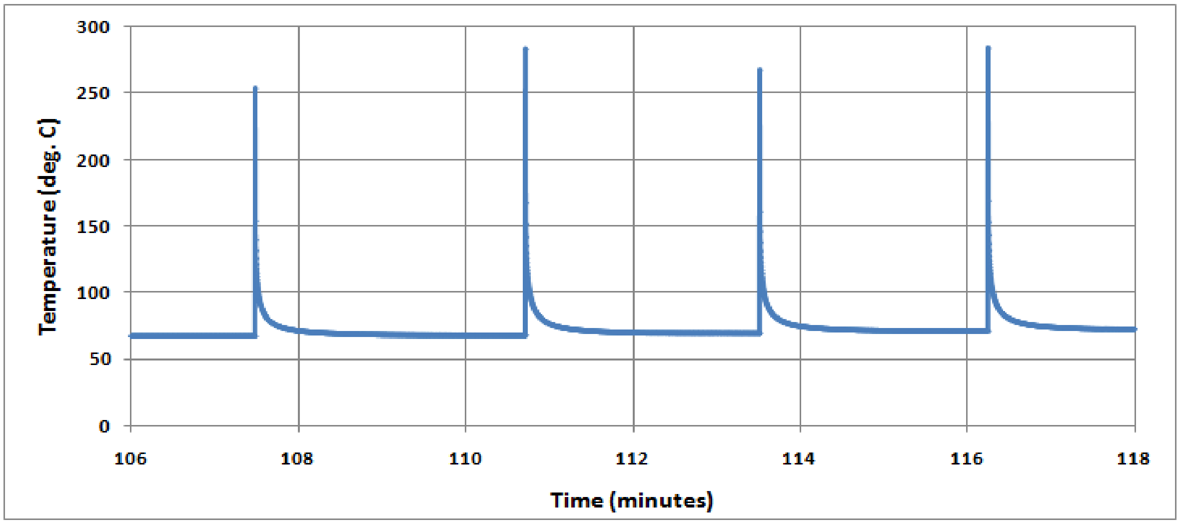

Figure 7. Measured internal bore temperature for four rounds. These high temporal and spatial resolution data are obtained by combining the TOF measurements from the rifled region and the through-the-barrel TOF data.

SUMMARY & CONCLUSIONS

We have demonstrated the ability to measure the local internal surface temperature using ultrasonic sensors mounted on the external surface of a large caliber gun. In this study, the ability to measure local temperature on the internal surface arises from the unique structure of the rifled region. The temperature localization relies on the echo "doublet" found in the rifled region. For the smooth bore region, determination of internal surface temperature and heat flux using a single interface echo in combination with inverse methods has been described elsewhere[5,6].

For the rifled region, the theory and laboratory experiments suggest that the conversion of measured ultrasonic TOF data relies on a single material parameter, $P_{pm,}$ the velocity-expansion coefficient. Best overall temperature estimates are obtained by combining the through-the-wall TOF data with the measurements from the rifled section. The measurement method has been demonstrated on large caliber guns in a live-fire operating environment. The ultrasonic technique has sufficient temporal response and sensitivity to be used to improve gun safety in situations where auto-ignition is of concern.

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