Test Apparatus Design for Assessment of Techniques Used to Mitigate Thermal Transient Response of Blast Pressure Transducers

Written By
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TEST APPARATUS DESIGN FOR ASSESSMENT OF TECHNIQUES USED TO MITIGATE THERMAL TRANSIENT RESPONSE OF BLAST PRESSURE TRANSDUCERS

by

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USED TO MITIGATE THERMAL TRANSIENT RESPONSE

OF BLAST PRESSURE TRANSDUCERS

Project Approved:

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(Supervising Professor)

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TABLE OF CONTENTS

List of Illustrations

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I. Introduction

This project develops a method for the experimental testing of the effectiveness of various thermal barriers on reducing false readings caused by the exposure of pressure transducers to transient heat fluxes such as those found in a blast environment. Understanding the effects of blast environments is important in the areas of national defense, homeland security, mining, and countless other areas where the effects of explosives is highly critical.

During the first few milliseconds of a blast a shock wave propagates away from the epicenter of the blast. This shock wave can be seen leading the left edge of the blast in the following sequentially shot figures 1 and 2:

Figure 1

Figure 2

The propagating shock wave encompasses the surrounding objects well before the fireball that is most typically associated with blasts. This shock wave not only contains the vast majority of the destructive energy contained in an blast but also produces a significant heat flux. This heating can result in thermal expansion of the measuring transducer that will be used for blast characterization. This heating expands the quartz piezoelectric crystal stack within the transducer, resulting in the artificial negative pressure reading explained below.

Quartz pressure transducers are typically constructed of a piezoelectric quartz crystal stack that is preloaded in compression between two masses that are then welded into place within a cylindrical body. When a transient heat flux is absorbed by the transducer this body experiences thermal expansion, resulting in a release of some of the preload holding the crystal stack together. This is the cause of false negative pressure readings that often accompany blast testing.

Negative pressure readings are currently minimized by placing various thermal barriers over the front diaphragm of the pressure transducer assembly. Typical examples of thermal barrier materials include a layer of black electrical tape, ceramic coatings, thermal greases, or the use of room-temperature vulcanizing silicone rubbers. Additionally, the coefficient of thermal expansion specific to the material of which the transducer is constructed can also serve a very important roll in minimizing the effect of false negative pressure readings. This is particularly true because quartz has a very small coefficient of thermal expansion relative to the typical metals that surround it within the transducer.

The exact heat flux and the duration of the heat flux are typically unknown variables in a blast test. Additionally, the false negative transducer pressure response occurs shortly after the beginning of the positive pressure reading, making it impossible to isolate the negative error signal.

This experimental apparatus and procedure operates at ambient pressure under a known heat flux and implements an approximate step function of heat flux exposure to the pressure transducer being tested for a controllable and measurable duration of time. This allows for a definitive method of quantifying the effectiveness of thermal barriers in minimizing the effects of known heat flux transients of controlled characteristics to pressure transducers.

II. Experiment Setup

An experimental setup was created to "chop" a propane torch flame with a stainless steel wheel while capturing the false pressure response of the pressure transducer. The setup was designed to allow for the torch to be slid closer or farther from the pressure transducer, and to be pivoted to one side. Moving the propane torch fore and aft allowed for another method of manipulating the heat flux that is ultimately exposed to the pressure transducer. A heat flux calorimeter is utilized to measure the heat flux being exposed to the transducer. Pivoting the torch to one side allows the operator to swap sensors and install the pressure transducer to be tested after heat flux measurement without turning the torch off. This is crucial to ensure that the heat flux readings are an accurate representation of the heat flux being exposed to the pressure transducer.

A photogate is utilized as a reference point in time to establish the instant at which the transducer is exposed to heat flux. The photogate also allows for a precise way to measure pulse width. The signal of the photogate and the transducer being tested is fed into a digital oscilloscope that is single-triggered by an external circuit which closes as soon as the torch flame is fully uncovered by a fulcrum arm assembly. A figure of the entire experimental test assembly can be seen in figure 3.

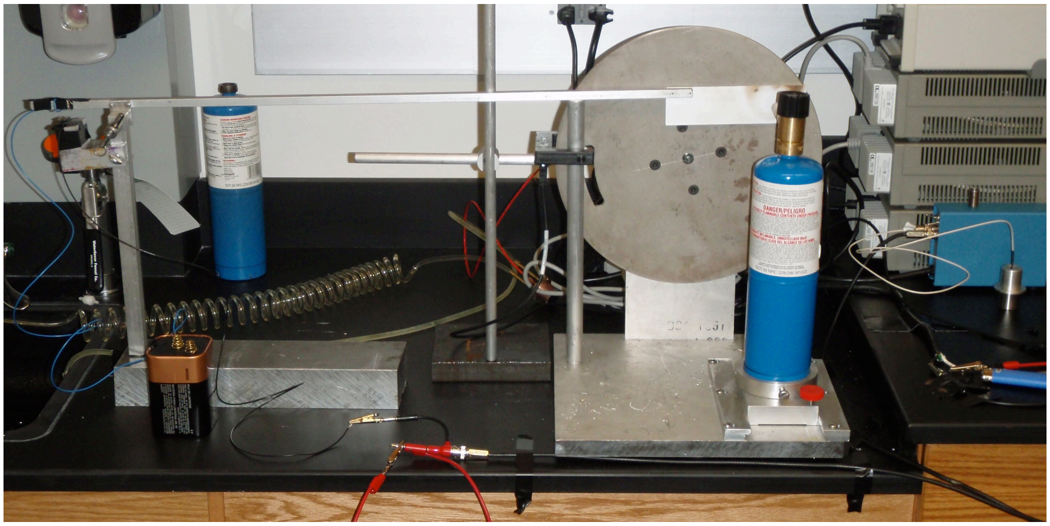

Figure 3

III. The Flame Chopper Wheel Assembly

The flame chopping wheel assembly is constructed with two slits of equal arc-length and radial distance from the center that are placed at opposite sides of the circular wheel. An adapter was fabricated to mount to the central spindle of the motor, allowing for four bolts to fasten the wheel securely to the adaptor. Two wheels were utilized, one with slits of arc-length one inch and the other with slits of arc-length three inches. This allows for more variation in duration of torch-transducer exposure. Both wheels were cut from quarter inch 304 stainless steel and are twelve inches in diameter. The wheel is attached at the center to a DC motor. The motor was selected in conjunction with a DC motor controller to allow for an adequate range of wheel speeds. A Dart 65E20-12 DC motor controller was selected based on the ability to regulate speed at a 30:1 ratio using a potentiometer. The Dayton 4Z144B motor selected operates at a maximum speed of 1750 rpm under a twelve volt DC power supply and will consume 6.83

amps at full load. It is important to know that the low motor speed is limited by the controller and motor itself, while the high motor speed is first limited by balancing issues within the wheel assembly. This particular motor and controller pair were selected along with the two wheel slit lengths in order to give a range of heat flux exposure times ranging from 2-20 ms, representative of a blast environment. The base of the entire flame chopper wheel assembly is placed on rubber feet to minimize vibrations caused by wheel balance issues. Additionally, the motor was selected to provide adequate torque for this application. A figure of the flame chopper wheel including the photogate and the torch cover located on the end of the fulcrum arm assembly can be seen in figure 4.

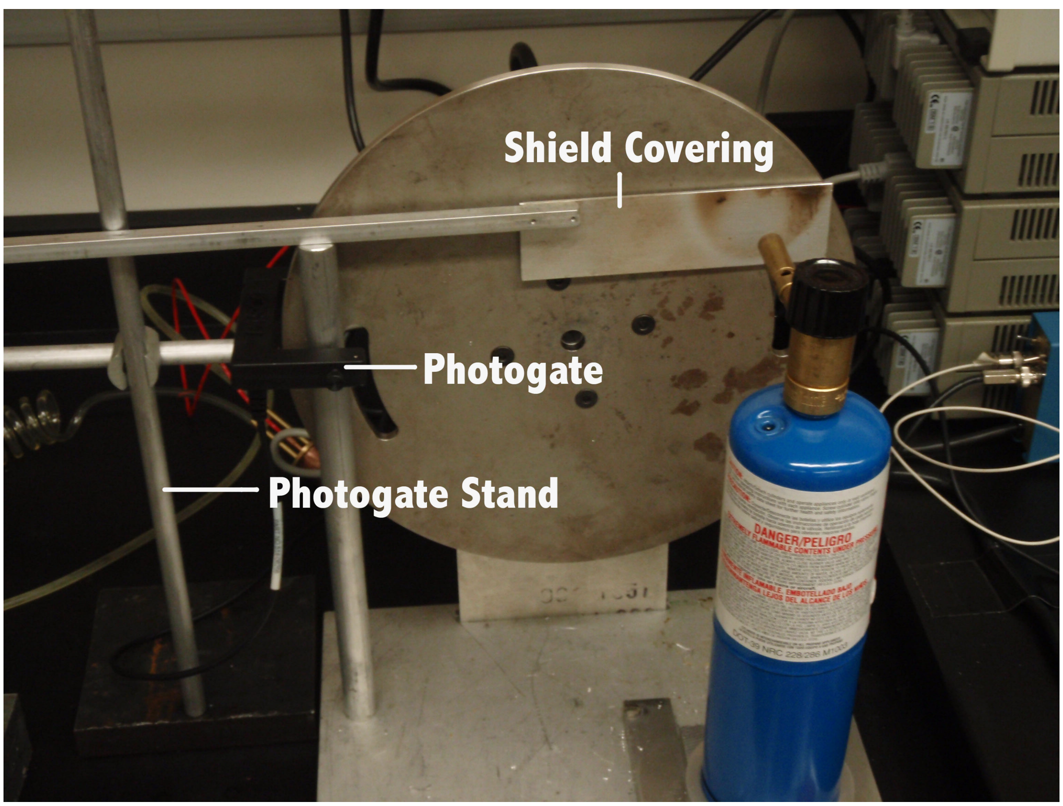

Figure 4

IV. The Photogate Assembly

A Pasco Model ME-9471 photogate is utilized to allow both for the accurate measurement of heat flux exposure with respect to time and to serve as a reference on the oscilloscope in which to determine the exact instant on the digital capture when the torch and transducer are exposed to each other. The photogate also allows for a more accurate measurement of wheel rotation than a mechanical tachometer. The photogate has a rise time of less than five hundred nanoseconds and a fall time of less than fifty nanoseconds. The output of the photogate is fed to the B-channel on the oscilloscope, and is represented by a zero to five volt square wave that shows a high voltage when a slit is passing through the photogate, allowing for the gate's infrared sensor to see through the slit. This square wave signal allows not only for a more accurate determination of the time which the pressure transducer will be exposed to the heat flux of the torch flame but also to allow the operator to locate the precise instant where torch-transducer exposure begins. The photogate is mounted onto a vertical rod on a separate steel base. The vertical rod has a protruding horizontal rod on a slider to which the photogate itself is mounted. This allows for vertical and horizontal positioning of the photogate and for it to be fastened securely in place with set screws. The photogate stand assembly can be seen in figure 4. The photogate can be seen in figure 5 aligned properly with the slit of the wheel in the horizontal direction.

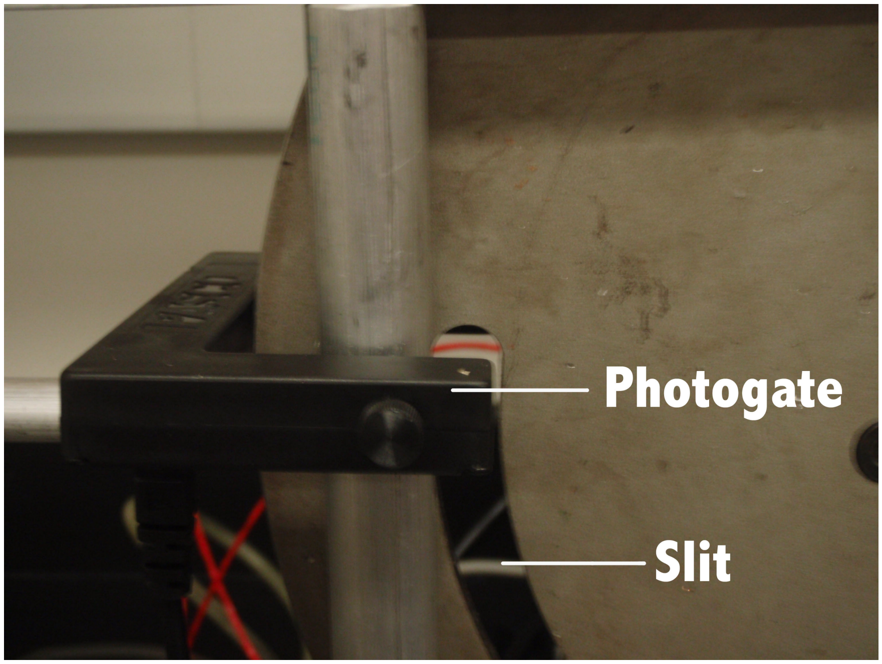

Figure 5

Photogate positioning is absolutely critical in establishing a correct interpretation of the data. The photogate must be positioned in such a way that it either opens or closes at the precise instant that the opposite slit is opening, exposing the torch to the pressure transducer. This position is dictated by the physical parameters of the experimental setup and allows for the simple addition or subtraction of the square waves pulse width in the time domain in order to establish the precise moment of torch-transducer exposure.

V. The Fulcrum Arm Assembly

It is necessary to isolate the pressure transducer from the heat source prior to the capture of data. That is to say that the pressure transducer must not see the torch until the instant in time in which the test occurs. In order to achieve this isolation the torch flame must be covered. The difficulty lies in the fact that this cover must be removed fully from impeding the torch flame in an amount of time less than one-half of one full wheel rotation. At the higher end of rotational speeds used, 900rpm for example, the wheel is making fifteen complete rotations per second. This means that the slot cover must be completely removed in a time of less than 33.3 milliseconds. This is an incredibly short amount of time in which to move a mechanical object. To put this amount of time in perspective, simply dropping a piece of metal through the opening between the torch flame and the wheel assembly would prove far too slow.

In order to move the slit cover in the amount of time required it is necessary to utilize mechanical amplification. A fulcrum assembly comprised of a simple lever with a known pivot point allows for a very small motion on one end to translate into a very large motion on the other. The manually actuated arm of the fulcrum assembly is four inches long, while the opposite arm extends twenty nine inches from the pivot point to the center of the torch flame. This results in a requirement of moving the actuated lever less than two tenths of an inch in order to move the torch cover upward an inch.

VI. Triggering Methods

In order to trigger the scope prior the the transducer being exposed to the torch, an external trigger is utilized. An external trigger circuit was designed in such a way that when the fulcrum lever is depressed fully, the oscilloscope is triggered. At the manually actuated end of the fulcrum assembly is a stop that makes contact with the fulcrum when the lever is pressed down. This stop is placed at a vertical distance that allows for it only to be hit when the slit cover is fully moved out of the way. At this interface lies an electronic contact. Closing this contact completes an electrical circuit with a 6V battery that is fed to the external trigger of the Infinium scope. This setup allows for the scope to be set into an armed mode while the experiment is set up, and while the transducer is shielded from the heat flux of the torch. At the moment that the shield covering the torch is removed, the contacts on the fulcrum arm assembly complete the circuit, and the oscilloscope begins capturing data. The shield covering the fulcrum arm can be seen in figure 4.

VII. Transducer Material

The materials that the transducer diaphragm and body are constructed from play a very important role in minimizing the effects of thermal transients on pressure transducer readings. Invar, a nickel-steel alloy, is known for having an exceptionally low thermal coefficient of expansion, and is therefore an ideal material for the construction of pressure transducers. The linear coefficient of thermal expansion for Invar typically falls into the range of 0.4-0.9 ppm/ºF. For comparison, the linear coefficient of thermal expansion for 1040 steel is 6.5 ppm/ºF.[1] Due to Invar's low thermal coefficient of expansion quartz transducers comprised of both Invar diaphragms and bodies are expected to show very little response to heat transients relative to their full scale pressure ratings.

VIII. Transducer Sensitivity and Rotating Slits

It became evident through the process of this experiment that highly sensitive pressure transducers are indeed able to detect the minute pressure changes that occur when the slit located in the flame chopper wheel assembly passes by the front of the pressure transducer. This effect is particularly obvious in the PCB Piezotronic 113B38 and 113B28 pressure transducers, each having a 50psi max pressure and relative sensitivities of 103.4 mV/psi and 118.2 mV/psi respectively. This effect is particularly problematic due to the entirely Invar construction of both transducers, as Invar minimizes the effect of thermal expansion. As a result the relatively small false pressure readings seen under exposure to heat flux correspond to less than half of a psi, and are easily distorted by the effect of the pressure changes inflicted on the transducer due to the slit passing in front of the transducer. Subsequently this experimental setup is more conducive to evaluating the effect of thermal barriers on pressure transducers of differing materials. In such transducers, the false negative pressure reading dwarf the small transient pressure readings caused by the turbulent air in front of the transducer, allowing for measurements to be made.

IX. Heat Flux Calorimeter Readings

A heat flux calorimeter was utilized in order to measure the heat flux produced by the propane torch at the same distance from the tip of the torch that the pressure transducer is to be placed. A Vatell 1000-0 circular foil heat flux calorimeter was custom ordered to withstand the typical heat flux produced by a propane torch -- up to a sustained

10 BTU/ft^2 sec. The heat flux calorimeter selected is water cooled, requiring a constant flow of water through it's fittings. The water is used to cool the outside wall of the gage, allowing for thermocouples to read the temperature gradient across the gage face. During the course of this experiment it became evident that the heat flux calorimeter's output seemed to fluctuate several psi. This problem was solved by ensuring that the torch tip comes into direct contact with the heat flux calorimeter at the center of the calorimeter's front face. This is achieved by a combination of increasing flame strength and moving the torch closer toward the wheel face. Failure to properly align the torch can result in wildly variable or overly high temperature readings due to a higher heating of the side of the calorimeter rather than the center of the face. It should be noted that after properly centering the torch flame on the heat flux calorimeter, further readings fluctuated on the order two percent of the full scale sensor range, allowing for an acceptable reading of the heat flux. This is due to a proper gradient between the center and outside edge of the sensor being achieved.

X. Experimental Verification and Interpretation

In order to ensure that the data being captured accurately portrays the magnitude and response shape of the false negative transducer pressure readings as a result of a thermal heat flux input, it is important to consider the adequacy of the time constant that is being used in the quartz pressure transducer system. In this case that includes the time constant within the PCB Piezotronics ICP transducer itself and the time constant in the amplifier due to AC coupling. The PCB Piezotronic 102A04 transducer being tested in the figure 6 has a time constant of greater than one hundred seconds. It is important that both of these time constants be long enough to allow for an accurate measurement of the thermal response pulse being recorded without the time constant decaying the signal back towards zero. One method of testing this is to quickly tap on the transducer while observing the starting and ending voltage. If the initial voltage and final voltage are on the same level, then the specified pulse width lies well within the operable range of the time constants of the system. The result of this test can be seen in figure 6.

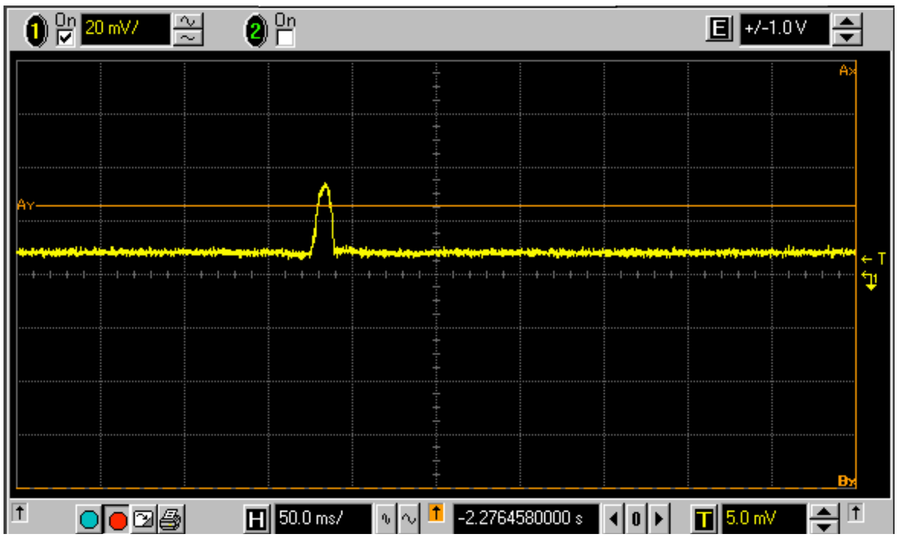

Figure 6

The pulse width of the above pulse is approximately twenty five milliseconds and it demonstrates a voltage level after the pulse that is equal to the voltage level prior to the pulse--indicating that neither the time constant of the scope nor the pressure transducer is interfering with the measurement of a pulse of this width. This is significant due to the fact that measurements of the magnitude of the transducer's output are only taken for a maximum of thirty milliseconds following the initial exposure of the torch to the pressure transducer. This indicates that the data generated during this test fall safely within a range that is not effected by the time constants of the pressure transducer system.

Another consideration that may affect data acquisition is the dynamic pressure introduced across the face of the transducer when the slot in the wheel passes by. In order to isolate this effect, a transducer was placed into its holder as usual, and the wheel was spun up to speed. The torch was not lit; instead, data was acquired constantly under no exposure to transient heat flux and the output of the pressure transducer was observed. This test indicated that the PCB Piezotronics 102A04 transducer being tested did not respond to the small dynamic changes in pressure caused by the rotating slit.

XI. Experimental Procedure

- Ensure that the connections between the flexible tubing, heat flux calorimeter, and sink fitting are securely fastened.
- Turn on the flow of the cold water from the sink so that a solid stream of water emerges from the output flexible hose.
- Wait approximately ten minutes to both remove air bubbles from the line and to ensure that water temperature equalizes after flushing the old water out of the water lines of the building.
- Place the pressure transducer to be tested into the proper fitting with cables attached and power on any amplifier that will be used. The amplifier should be AC coupled. ICP transducers require a few minutes for the amplifier to balance and bring the output level down to an approximately zero volt level. The output of the pressure transducer's amplifier should be fed through a BNC cable into channel A of the oscilloscope.
- Place the heat flux calorimeter securely into the mount behind the flame chopper wheel.

- Verify that the alignment of the photogate relative to the point at which the transducer will be exposed to the torch flame is known and that the photogate's beam is indeed uninterrupted when the slit is located between the arms of the gate. This step is incredibly important and must be setup very carefully in order to attain interpretable results. Suggested positions include one where the photogate opens at the exact instant of torch-transducer exposure, or in such a way that the photogate closes at the exact instant of transducer exposure. In reality this gate can be placed anywhere along the wheel so long as the arc-length difference is known in order to back-calculate the time relative to the slit at which the torch is exposed to the transducer.
- Light the propane torch and adjust the flame with the regulator to the desired length. The position of the torch on the sliding track to and from the wheel is important. The torch must be positioned in such a way that the flame is not curling upwards at the point of contact with the heat flux calorimeter. Reverify water flow through the heat flux calorimeter and verify flame length and positioning by rotating the wheel manually so that the slit is exposing the heat flux calorimeter and rotating the torch while observing the setup from the side. The torch flame should make contact with the center of the heat flux calorimeter and should not be curving upward to the point where direct flame contact is being made to the outside of the heat flux calorimeter. Failing to do so will result in a false reading.
- Read the output of the heat flux calorimeter. This is best done using an oscilloscope, as the low voltage signal is particularly susceptible to picking up electronic noise which cannot be seen on a multimeter. The millivolt output of the heat flux calorimeter can be

compared to the transducer's calibration sheet in order to establish the heat flux that will be seen by the pressure transducer in subsequent tests.

- Ensure that the fulcrum arm assembly contact will make proper contact when the arm is depressed.
- Replace the heat flux calorimeter with the pressure transducer to be tested. The transducer should have already been placed into the proper adaptor and have cables connected. Additionally, the amplifier being used should have already been warming up for several minutes.
- Set the gain on channel A of the oscilloscope to a number representing approximately 2% of the full scale voltage particular to the pressure transducer being tested. Channel B gain should be set to a value of five volts per division. The oscilloscope should be configured to utilize an external trigger set to a level of +/- 3 Volts, single triggered, rising wave form.
- Connect the power to the DC motor controller and allow the wheel to get up to speed. This may take several minutes.
- Take a preliminary speed reading using a handheld tachometer. This speed can later be verified using the pulsewidth of the output of the photogate.
- Arm the oscilloscope and depress the fulcrum arm assembly quickly. It is not necessary to hold the fulcrum arm in the depressed position for more than a few seconds. Exposure of the torch to the pressure transducer for extended periods of time should be avoided as it can damage the electronics within the transducer.

- The oscilloscope should have captured the proper data. By looking for the next square wave pulse after the moment of triggering and adding or subtracting a pulse width depending on the physical location of the photogate as discussed earlier, the precise moment of the pressure transducer's exposure to heat flux can be found.

XII. Comparative Methodology

By utilizing the square wave output of the photogate that can be seen in green in the figure below, it is possible to find the exact instant of torch exposure to heat flux. In the case of the three inch slit arc length, the photogate is positioned is such a way that it opens at the exact instant that the slit of the same length on the opposite side of the wheel is closing the exposure between the pressure transducer and the propane torch. Therefore by measuring the pulse width shown in green, and then moving the falling edge cursor to a time prior to the leading edge cursor equal to the pulse width generated by the photogate, it is possible to pinpoint the exact instant of torch-transducer exposure. A horizontal cursor is then utilized to measure the voltage difference between the reference, the voltage prior to torch exposure, and voltages at subsequent intervals of time after exposure begins. Figure 7 illustrates how the cursors are utilized to pinpoint the exact instant of the transducer's exposure to heat flux.

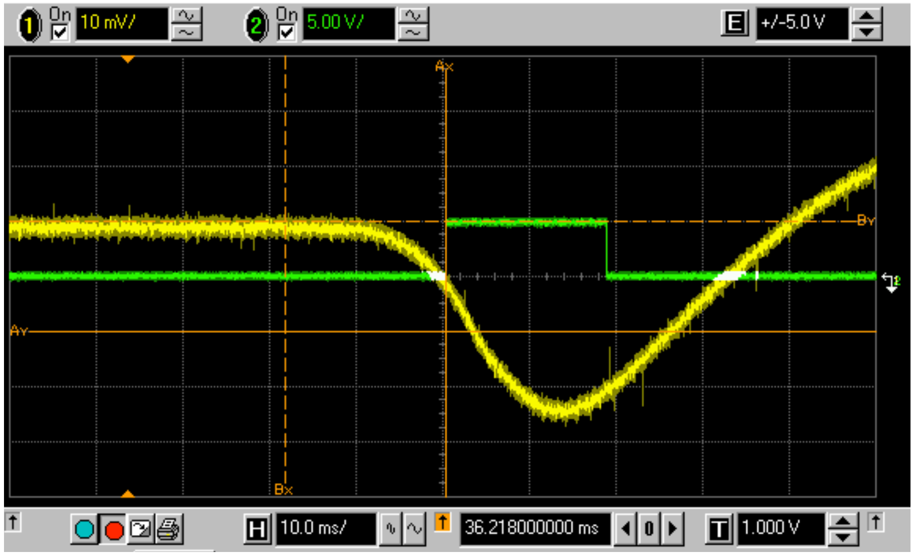

Figure 7

It should be noted that in real world applications the heat flux exposure does not end so abruptly, and therefore the area of interest is usually contained within the time of exposure. In this particular setup, as noted previously, the heat flux is applied to the transducer in an approximate square wave. While data points after the heat flux is removed from the transducer do not model what will be seen in real world applications where pressure is applied and heat flux tapers off slowly over time, they do allow for a quantitative and repetitive way of comparing the effectiveness of various thermal barriers.

XIII. Conclusion

The setup of this experiment and procedure allow for a means of quantitatively comparing the effectiveness of thermal barriers on pressure transducers of minimizing the effect of thermal transients. This is achieved by operating under a known heat flux, a known duration of transducer exposure to heat flux, and atmospheric pressure. This experiment is valuable because it allows for a repeatable way of quantifying the effectiveness of thermal barriers at mitigating the false negative transducer pressure readings typically experienced in blast environments. This will allow for a more accurate acquisition and interpretation of data , which will in turn result in a better understanding of the harsh conditions found in blast environments. By fully understanding and accurately acquiring the pressures achieved in blast environments, technology and structure designed to survive and or operate in blast environments will undoubtably improve.

Bibliography

[1] Callister, William D. Materials science and engineering an introduction. 7th ed. Hoboken, NJ: John Wiley & Sons, 2006.

ANALYSIS AND RESULTS OF
BLAST PRESSURE TRANSDUCER TESTING
UNDER EXPOSURE TO THERMAL TRANSIENTS

By

Justin Barrow

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TABLE OF CONTENTS

List of Illustrations

I. Introduction

This document presents the data found by conducting the experiment outlined in the paper *Test Apparatus Design for Assessment of Techniques Used to Mitigate Thermal Transient Response of Blast Pressure Transducers*. The experimental setup, design, and method can be found in detail in the previously mentioned document. This document will present the data collected during the experimentation and discuss various observations made with regards to said data.

II. The PCB 113B28 Pressure Transducer

The results of the test of the PCB 113B28 transducer will be discussed first. This sensor is constructed with a 17-4 stainless steel housing and an Invar diaphragm. The documented sensitivity of the 113B28 sensor used for this test is 118.2mV/psi, and the sensor's defined maximum range is 50psi. The sensor was first tested with no thermal barrier element in place over the diaphragm of the sensor. This configuration is referred to as *bare* during the remainder of the report. During the first experiment the heat flux of the propane torch was measured to be 4.6 BTU/ft^2-sec by a heat flux calorimeter placed at the same physical location as the pressure sensor. The duration of this exposure was experimentally measured by a photo-gate placed at the same radius as the sensor's diaphragm. A wheel with a slit was used to "chop" the torch flame. Two wheels were used, one with a significantly longer slit than the other. This allows for the sensor to be exposed for both a short and a long duration. This process is outlined more clearly in the previously referenced document.

It should be noted that the photo-gate's response, as seen in the oscilloscope screen capture, (Figure 1) opens at the instance in time that the heat flux exposing slit is shutting off torch-sensor exposure – that is to say that the sensor is initially exposed to heat flux at a time of one pulse width prior to the square wave seen on the image. In the following image, the sensor was first exposed to heat flux at a time denoted by the vertical Bx cursor, which is placed one pulse width prior to the initial photo-gate response (shown in green).

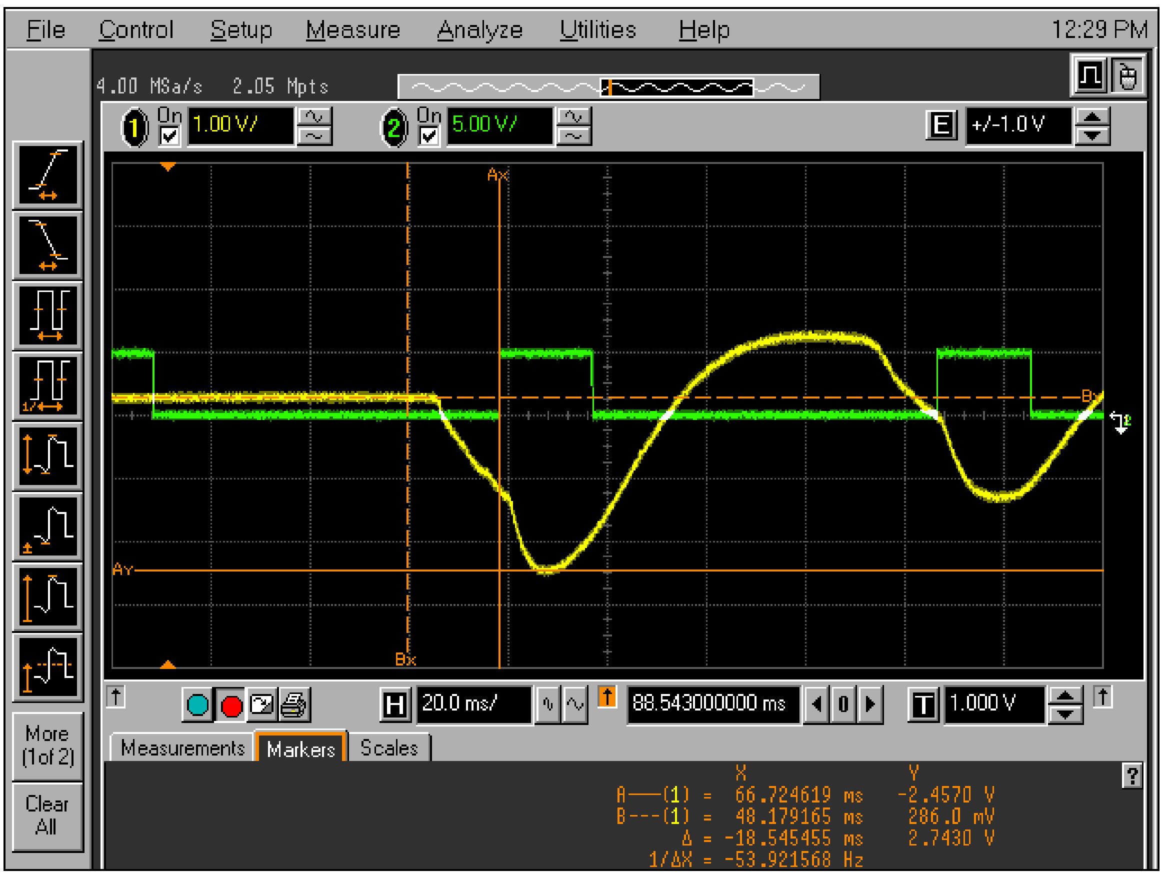

Figure 1 – 113B28 Exposure to 4.6 BTU/ft^2-sec for a duration of 18.54ms

In Figure 1, the response of the 113B28 sensor to a "long" exposure to transient heat flux is shown in yellow. The sensor was exposed for a duration of 18.5ms - controlled by the length of the slit on the wheel used as well as the motor's rotational velocity, as measured by the pulse width of the photogate's output, shown in green. The negative response following the sensor's initial exposure to heat flux demonstrates the false negative pressure reading typical of testing sensors using quartz sensing elements in blast environments. The exposure ends at the vertical Ax cursor. At this point in time the slit in the wheel has passed completely by the sensor and the torch is no longer interacting with the sensor. It should be noted that the sensor's negative response does not end here, as thermal energy is still traveling through the sensor's body and causing the sensor to expand. A maximum output of -2.629V was seen at a time of 25ms after the initial exposure of the transducer to the heat flux produced by the torch. This corresponds to a negative pressure reading equal to 44.5% of the sensor's full scale response, or -22.24psi. This illustrates the significant problems that false negative pressure readings cause when attempting to measure pressures in situations where a transient heat flux passes through the sensor, such as blast environments. The bare 113B28 sensor was tested five times under the "long" exposure time. The results of these tests can be seen below, note that each data series represents the results of a single test.

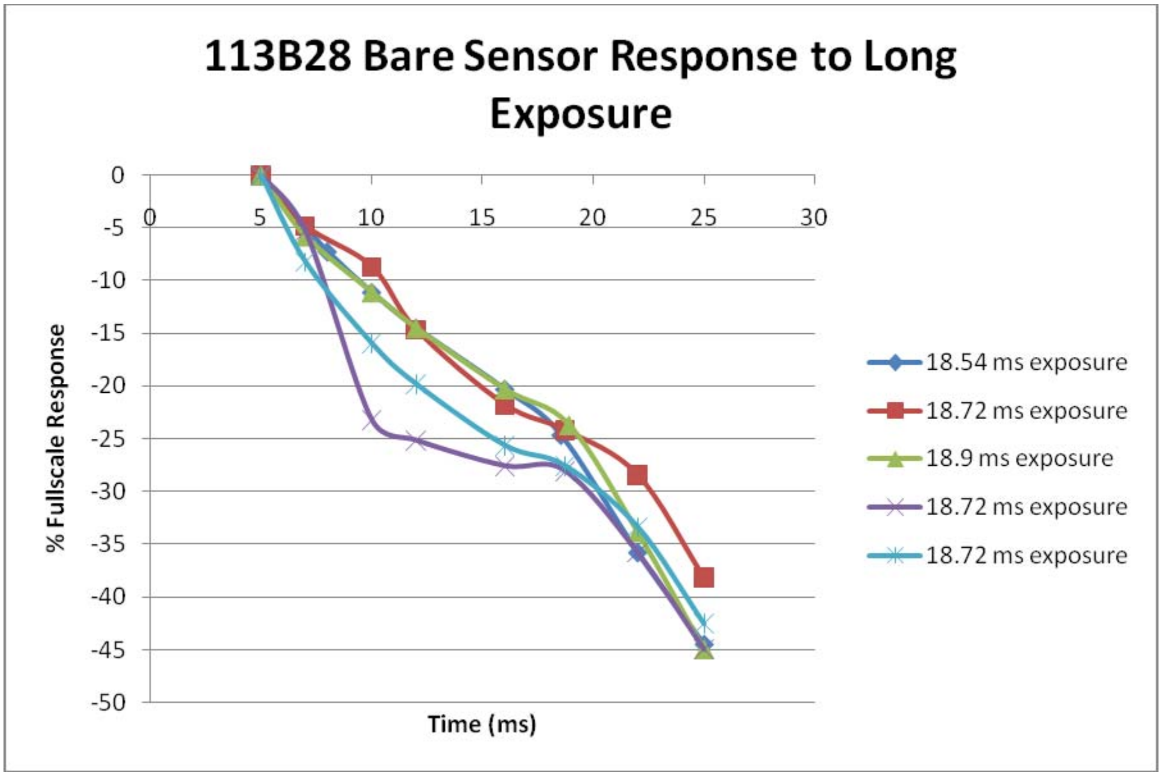

Figure 2 - Results of Bare 113B28 Long Time Duration Exposure to Heat Flux

Figure 2 illustrates that the results of these tests are highly repeatable. The effects of transient heat flux on a bare 113B28 sensor are significant and very apparent. These results show an average maximum negative pressure reading of greater than 40%. These data points were taken when the heat flux calorimeter measured an average heat flux of 4.69 BTU/ft^2-sec.

The bare 113B28 sensor was tested for a "short" duration heat flux by replacing the wheel on the test apparatus with another one containing a significantly shorter slit. The results of these tests can be seen in the figure below.

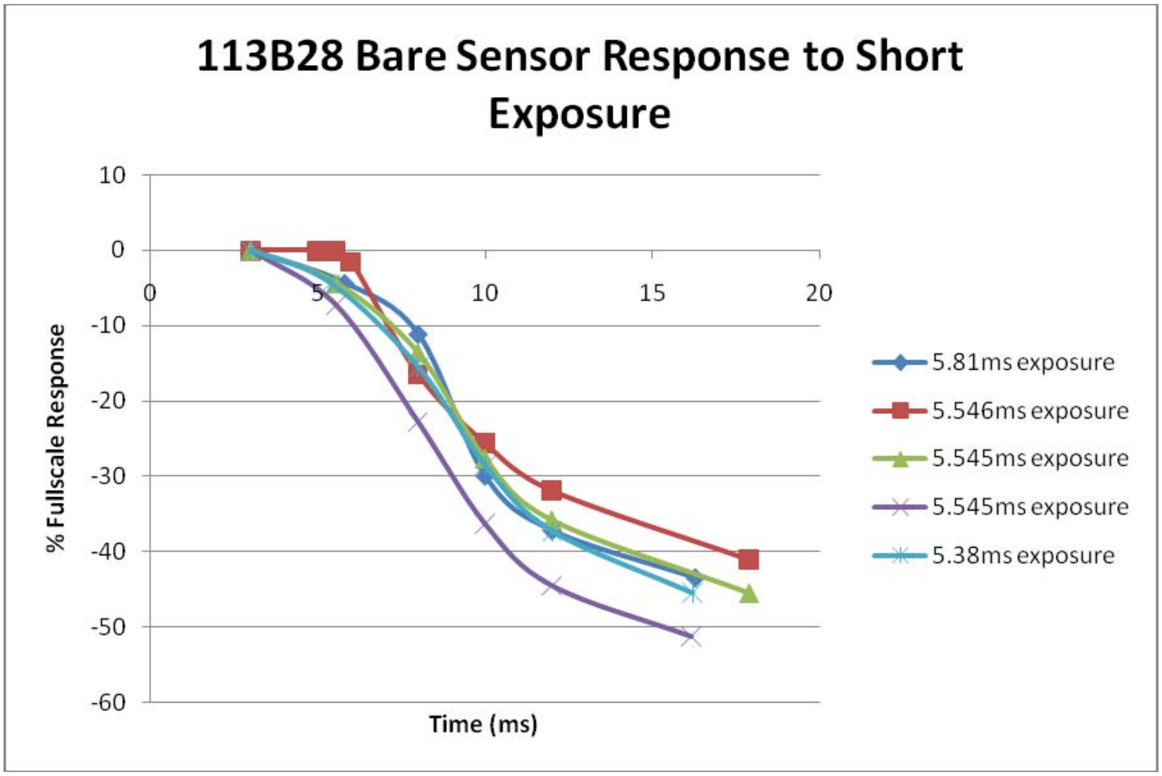

Figure 3 - Results of Bare 113B28 Short Time Duration Exposure to Heat Flux

Figure 3 demonstrates a high level of repeatability when measuring the results of a short duration exposure to a transient heat flux. Furthermore, the results of the short duration impulse show a very similar trend to that of the long duration heat flux exposure. Again, the 113B28 sensor demonstrates a maximum negative pressure reading greater than 40% of the sensor's full-scale output. These data points were collected when the heat flux calorimeter measured an average heat flux of 5.04 BTU/ft^2-sec.

The 113B28 sensor's diaphragm was coated with one layer of 3M vinyl tape ("black electrical tape"). Vinyl tape is traditionally used throughout the industry for the purpose of mitigating the phenomenon of pressure transducers reporting a false negative pressure reading when exposed to transient heat flux. The test was repeated for both a short and long duration exposure, the results can be seen below.

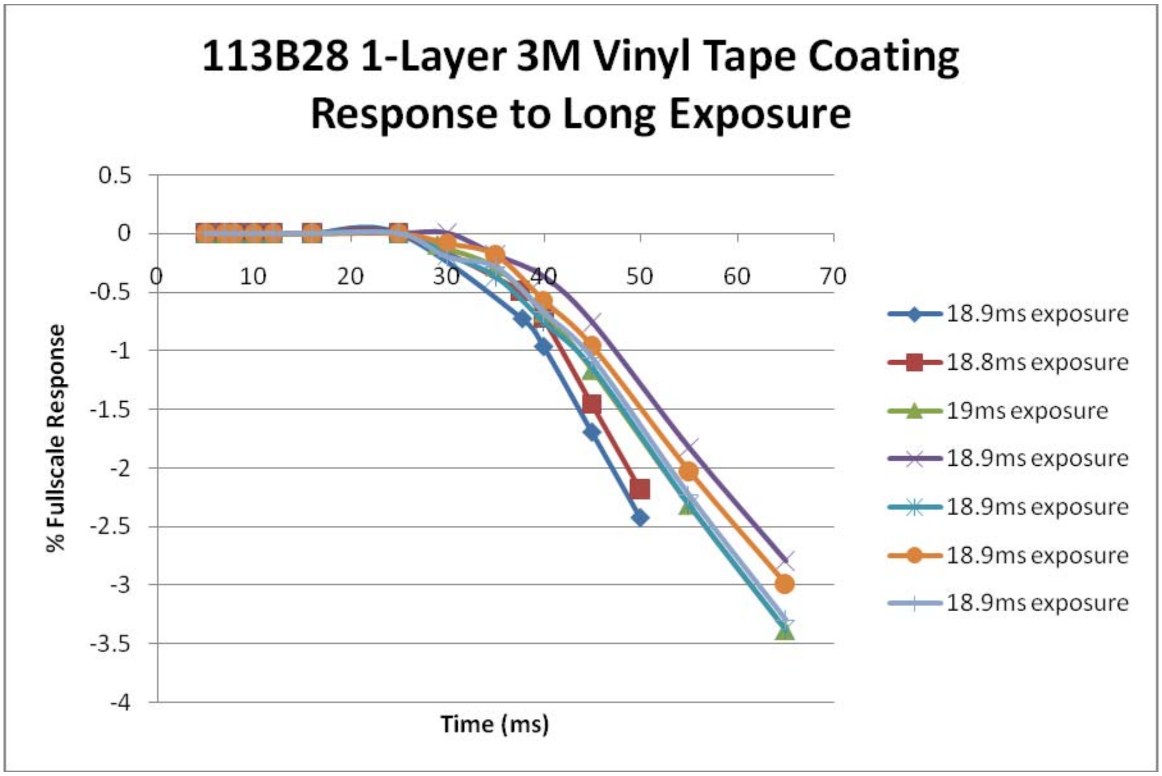

Figure 4 - Results of 1-Layer 3M Vinyl Tape Coating on 113B28 Long Time Duration Exposure to Heat Flux

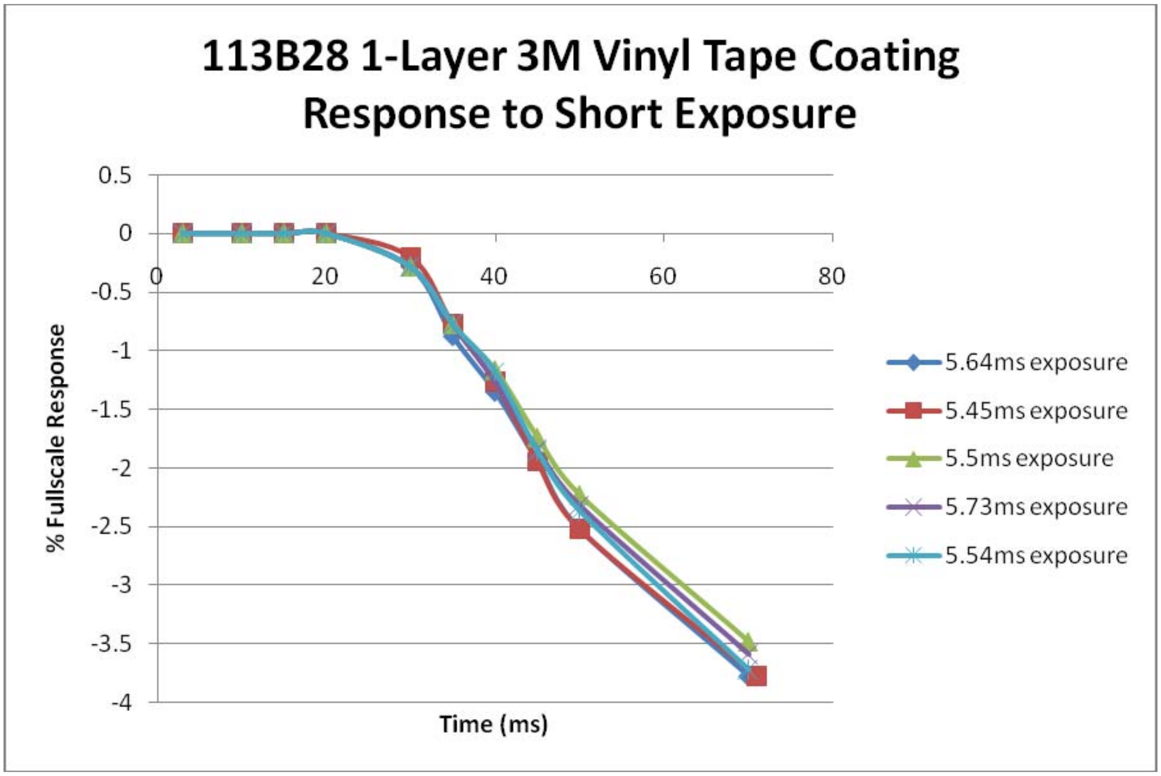

Figure 5 - Results of 1-Layer 3M Vinyl Tape Coating on 113B28 Short Time Duration Exposure to Heat Flux

Figures 4 and 5 again illustrate a similar and repeatable response while indicating a significant mitigation of the false negative pressure reading when compared to the results of the bare sensor. The short duration test was conducted with an average measured heat flux of 5.04 BTU/ft^2-sec, while the long duration test was conducted with an average measured heat flux of 5.39 BTU/ft^2-sec. A maximum false negative pressure reading of approximately 3.5% was seen when the sensor was tested with 1-layer of 3M vinyl tape applied over the diaphragm, while approximately 45% was typical for the same sensor tested with a bare diaphragm. These results hold true for both short and long duration exposures to transient heat flux.

A layer of red GE high temperature silicone RTV106 compound was allowed to cure over the diaphragm of the 113B28 sensor. The RTV was applied by creating a recess between the face of the transducer's mounting bracket and the diaphragm of the transducer itself. This void was measured with a micrometer prior to applying the liquid RTV. The red RTV was allowed to cure overnight and excess material was shaved off with a razor so that the exposed layer was flush with the front of the sensor mount assembly. The applied layer was measured to be 0.041 in. thick. The 113B28 sensor with RTV coating was tested under a short duration impulse, the results of which can be seen below.

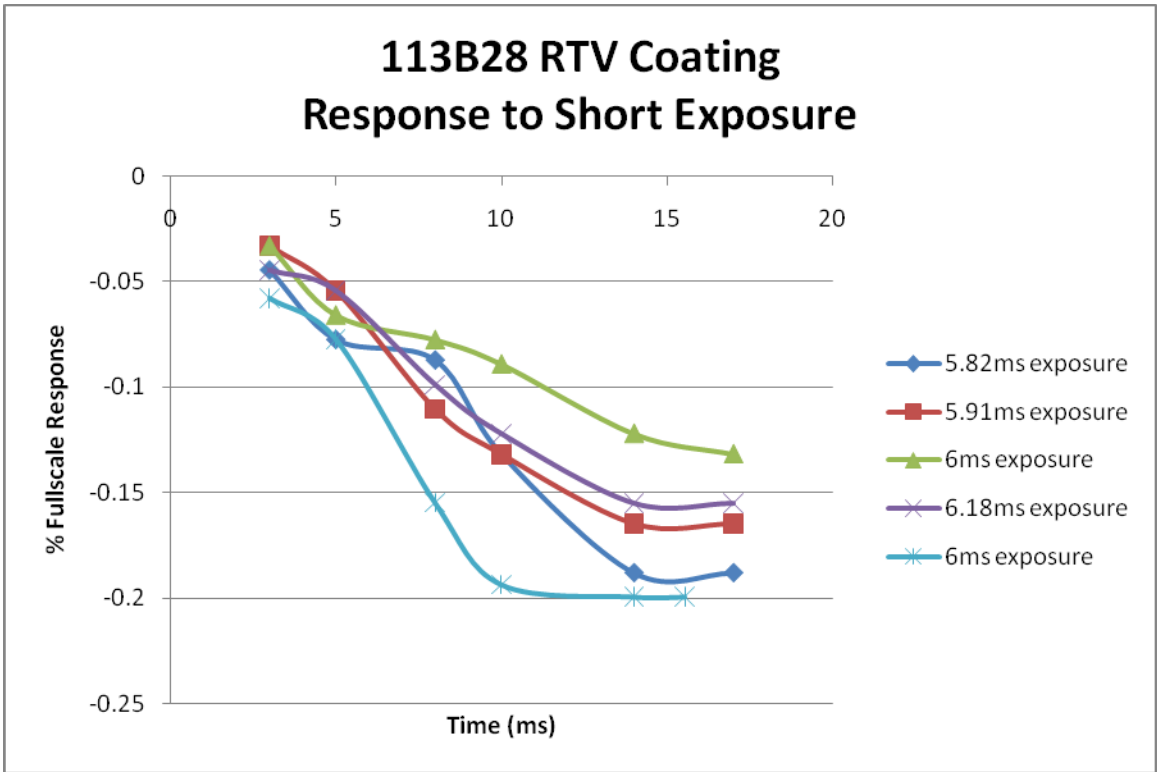

Figure 6 - Results of RTV Coated 113B28 Short Time Duration Exposure to Heat Flux

The response of the 113B28 sensor to transient heat flux when the diaphragm was coated with RTV was difficult to measure due to the fact that the maximum sensor output seen was less than 0.2% of the sensor's full-scale output when exposed to a heat flux measured at 6.0 BTU/ft^2-sec. This indicates an incredibly strong mitigation of the false negative pressure reading phenomenon typically exhibited by the sensor when exposed to transient heat flux.

III. The PCB 113B38 Pressure Transducer

The PCB 113B38 sensor is constructed of Invar, a nickel-steel alloy that is known for having a low coefficient of thermal expansion. Both the housing and the diaphragm of the 113B38 sensor are constructed of Invar. The idea behind Invar construction is that due to this low coefficient of thermal expansion the sensor body itself will not expand as drastically when exposed to a transient heat flux. This should minimize the expansion of the quartz stack within the sensor and therefore minimize the false negative pressure readings seen in typical steel constructed sensors. Testing the 113B38 sensor is incredibly relevant due to the fact that its physical dimensions are identical to the 113B28 sensor that was previously discussed. The major difference between the 1138B28 and 113B38 pressure transducers is the material of construction, allowing the results of the two sensors to be compared with one primary variable being changed. The results of both the short and long duration test for the bare 113B38 sensor can be seen below.

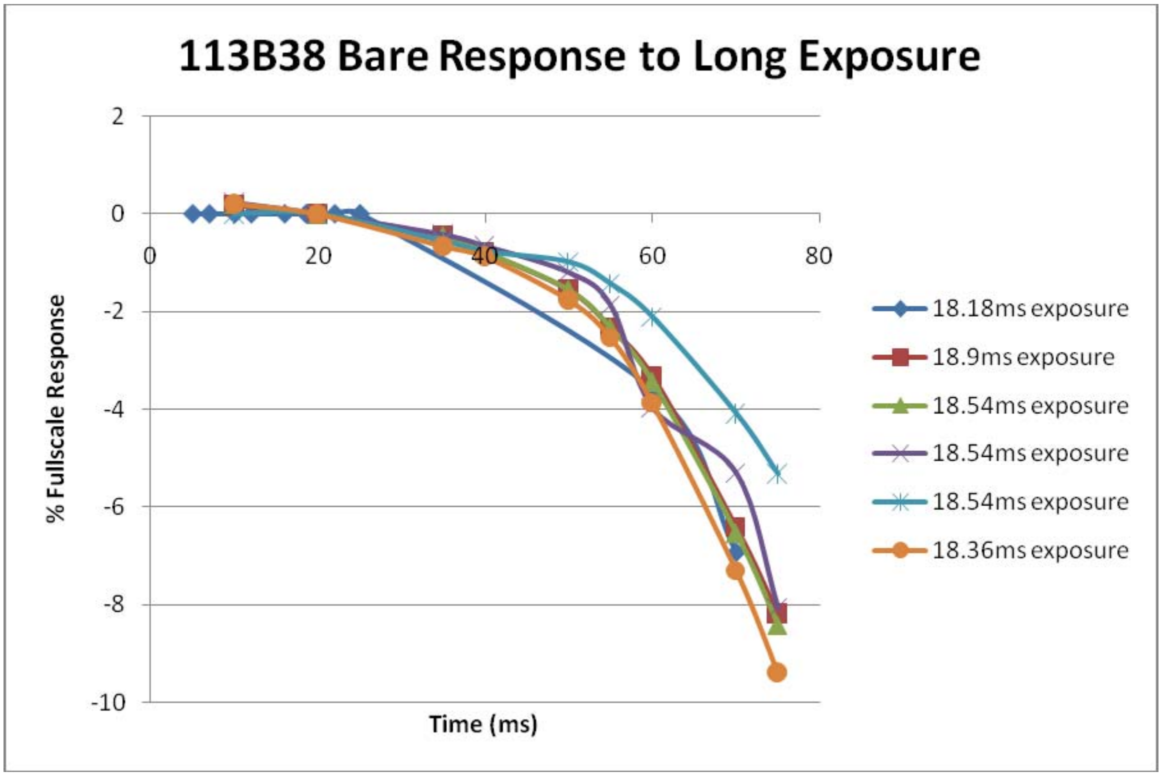

Figure 7 - Results of Bare 113B38 Long Time Duration Exposure to Heat Flux

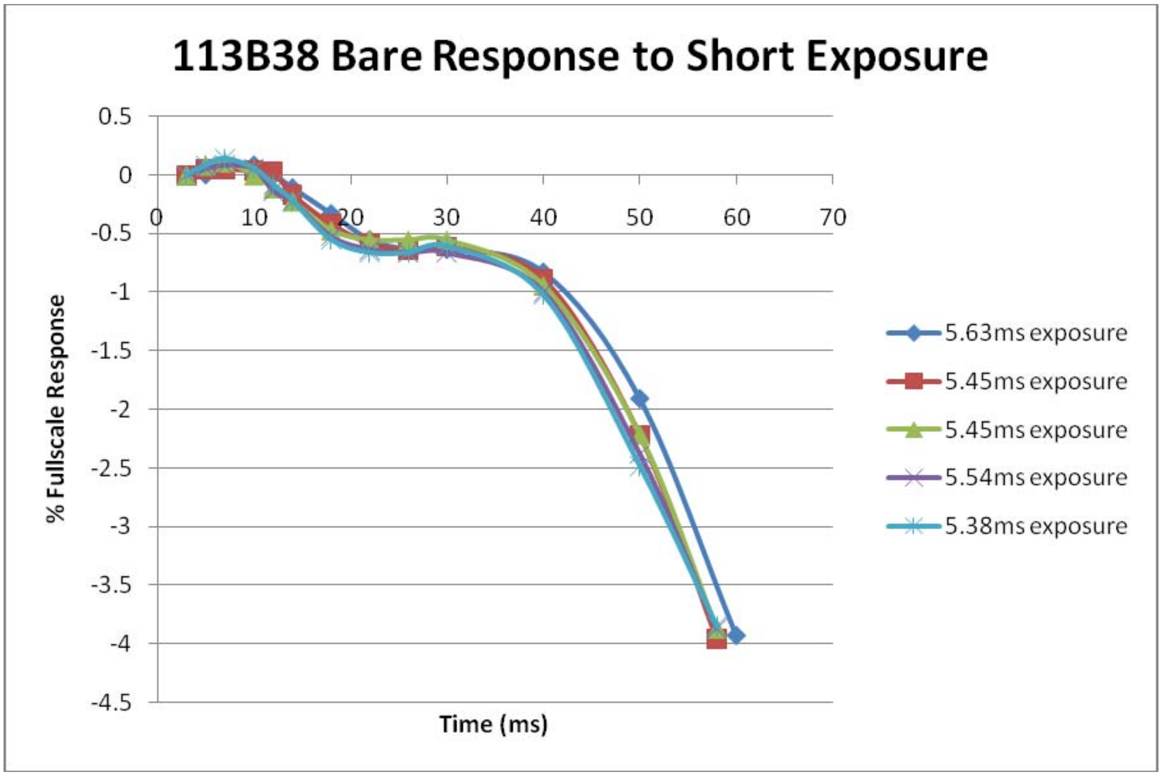

Figure 8 - Results of Bare 113B38 Short Time Duration Exposure to Heat Flux

Figures 7 and 8 illustrate a similar response shape with the long duration having a maximum average percent full-scale response of -8% while the short duration has a maximum average percent full-scale response of -4%. The short duration tests were conducted under an average heat flux of 5.22 BTU/ft^2-sec while the long duration tests were conducted under an average heat flux of 5.75 BTU/ft^2-sec. These responses are significantly smaller than those seen in the 113B28 sensor, indicating that Invar sensor construction is effective in mitigating false negative pressure readings.

IV. The Endevco 8530C-50 Pressure Transducer

An Endevco 8530C-50 MEMS bulk silicon pressure transducer was tested under a short exposure to the propane torch. This sensor is not the same ICP style as the others being tested; instead, it relies on a resistive bridge. The sensor tested had a factoryinstalled opaque, thermal grease barrier behind a screen over the front of the sensor's diaphragm. This thermal barrier was designed to reduce false negative pressure readings due to exposure to both light and transient thermal inputs. A Vishay 2311 signal conditioner was used to apply power and balance the sensor's resistive bridge. The results of the tests of this sensor configuration are plotted in the figure below.

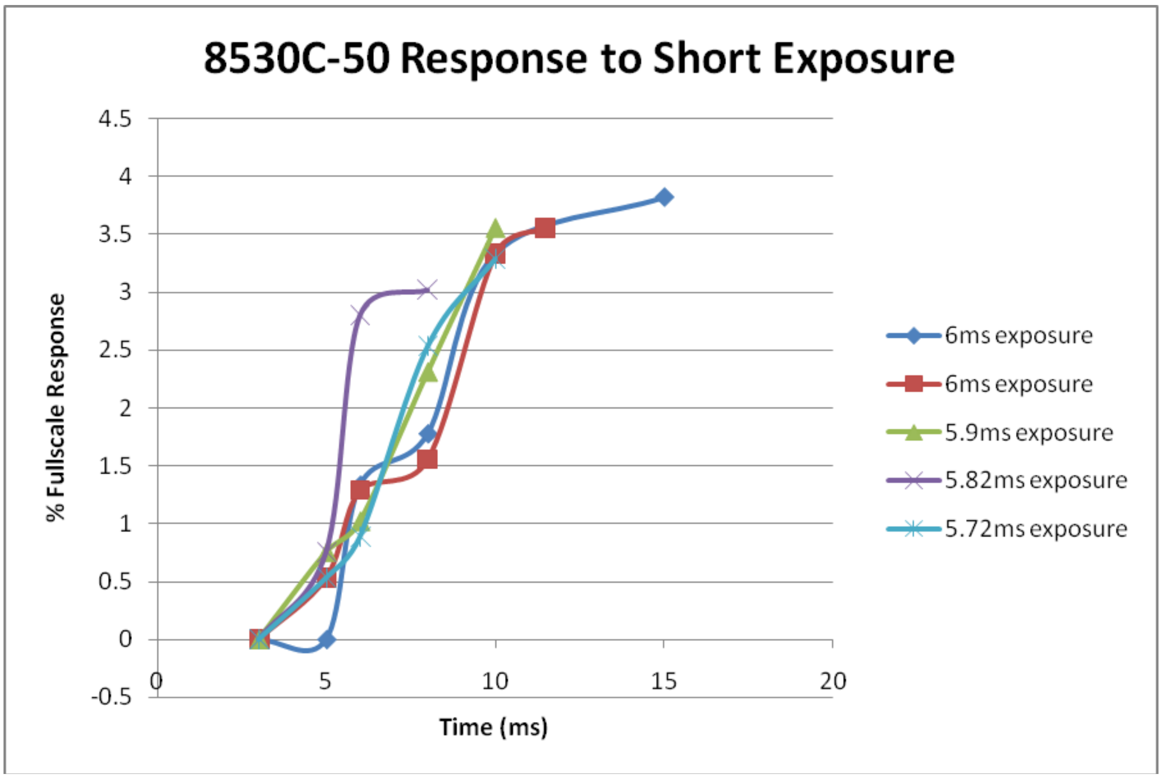

Figure 9 - Results of 5830C-50 Short Time Duration Exposure to Heat Flux

The 8530C-50 demonstrated a positive response to heat flux, a stark contrast when compared to the ICP based sensors.

V. Comparisons and Conclusions

This experiment demonstrates the effectiveness of various techniques at mitigating the false negative pressure readings typically seen when utilizing ICP pressure transducers in environments where transient heat fluxes are exposed to the sensor's diaphragm such as blast instrumentation. By controlling the variables of heat flux and exposure time, the effectiveness of various techniques can be quantitatively compared. It is easier to compare the results of each test with one another by graphing the percent full-scale sensor voltage output versus time. The combined graphs presenting the data acquired from the 113B28 and 113B38 sensors can be seen below. It is important to reiterate that the 113B38 sensor is physically identical to the 113B28 sensor except for its material of construction. This allows for a direct comparison to be made between the two sensors.

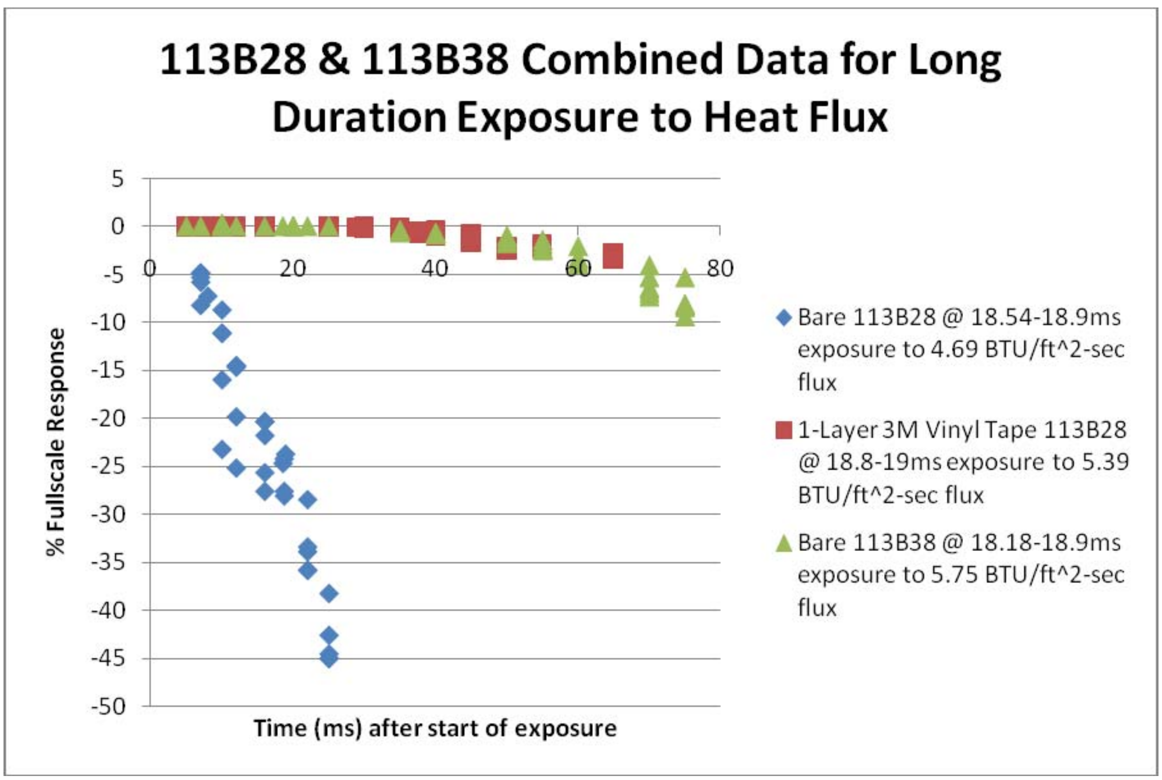

Figure 10 - Combined Results of 113B28 & 113B38 Response to Long Duration Exposure to Heat Flux

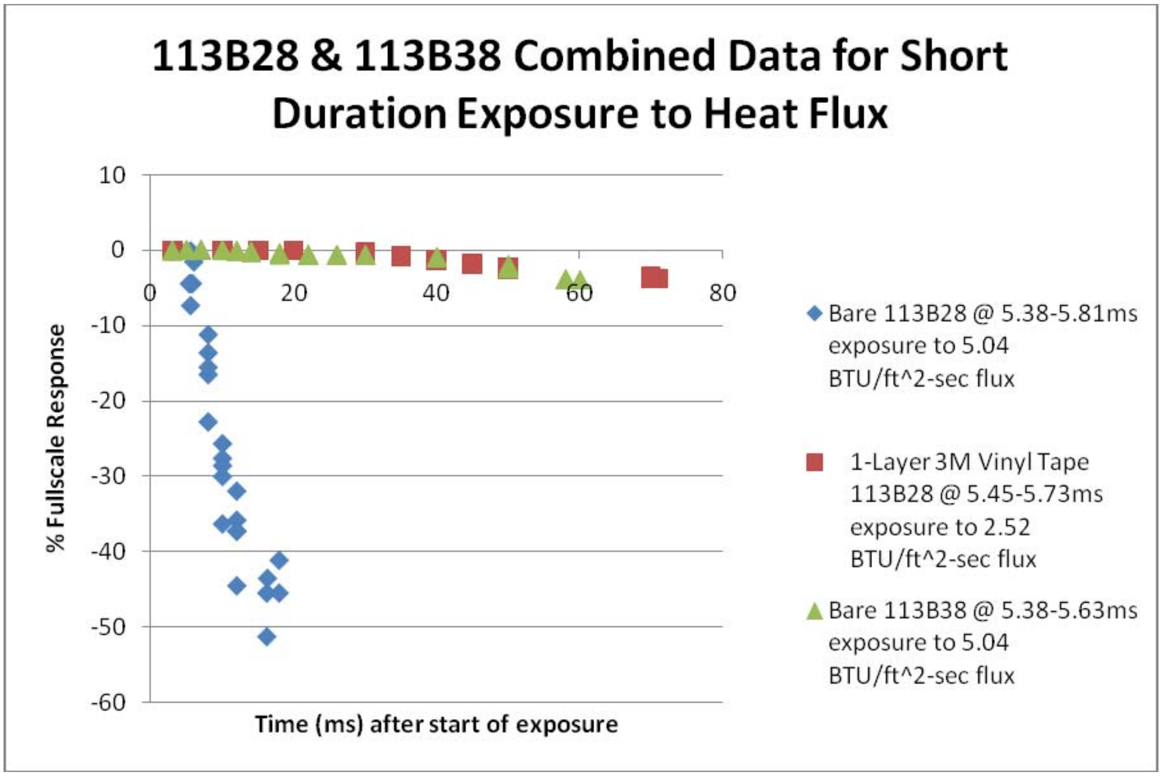

Figure 11 - Combined Results of 113B28 & 113B38 Response to Short Duration Exposure to Heat Flux

The data presented in Figure 10 and Figure 11 suggests a high level of repeatability between samples. A similar trend can be seen when observing the response of both the 113B28 and 1138B38 sensors for both the short and long duration exposures. These data clearly indicate the difficulties inherent in achieving accurate pressure readings in environments where the sensor diaphragm is exposed to transient heat flux. The bare 113B28 sensor exhibited a very large false negative pressure reading of greater than 40% of its full-scale output capability. This effect was significantly mitigated by adding a single layer of vinyl tape to the diaphragm of the sensor assembly. The percent full-scale output of the 113B28 sensor with one layer of 3M vinyl tape over the diaphragm demonstrated a very similar response to that of the 113B38 sensor constructed of all Invar. Both displayed a negative output corresponding to less than 2.5% full-scale response at a time 40ms after the initial exposure of the sensor to heat flux. These data suggest that vinyl tape provides a similar level of effectiveness at mitigating false negative pressure readings caused by thermal transients as that of Invar sensor construction. By coating the diaphragm of the sensor with red RTV the false negative pressure readings present in the 113B28 sensor are further mitigated -- a voltage corresponding to less than 0.2% of the sensor's full-scale output was measured. The resistive bridge based Endevco 5830C-50 sensor demonstrated a 3-4% full-scale response, but this time in the positive direction. This response is comparable in magnitude to the response seen by the 113B38 Invar constructed ICP sensor. Each thermal barrier method tested proved effective in mitigating the false pressure reading phenomenon. By utilizing a similar experimental setup one is able to quantify the effectiveness of thermal barriers at mitigating this phenomenon and choose a cost effective solution that provides a sufficient amount of mitigation.

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