NEW INNOVATIONS IN SHOCK DIAGNOSTICS & ANALYSIS USING HIGH-SPEED MULTI-POINT VELOCIMETRY (VISAR)

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Short duration, high amplitude shock waves and other high-speed motion generated by explosives; high-energy plasmas; and slapper detonators are difficult to measure due to their fast reaction times. One measurement tool frequently used is VISAR (Velocity Interferometer System for Any Reflector). VISAR is an optical-based system that utilizes Doppler interferometry techniques to measure the complete time-history of the motion of a surface. This technique is gaining worldwide acceptance as the tool of choice for measurement of shock phenomena. However, one limitation of VISAR is that it can only measure one point on a surface. The new high-speed Multi Point VISAR remedies most of the single point VISAR's limitations by using multiple fiber optics to send and receive Doppler information from a target. The receiving fiber optics are bundled together and the light is routed through one interferometer cavity. The fiber optic bundle image is separated into single fiber optic images where the Doppler information is individually analyzed. Multi Point VISAR allows the user to measure multiple events, then temporally correlate the shock arrival time as well as shock amplitude history. This paper will discuss some of the new VISAR developments. Shock planarity, amplitude, and simultaneity data will also be presented.

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VISAR BACKGROUND, THEORY OF OPERATION

The primary components of VISAR (Velocity Interferometer System for Any Reflector) are a single frequency laser, interferometer cavity, high speed photomultiplier tubes and recording devices (**FIGURE 1**). The laser used for the Multi-

Point VISAR (MPV) is a single frequency-frequency doubled Nd:YVO (Neodymium-doped Yittrium Vanadate Oxide crystal) operating at up to 5 Watts, continuous wave (CW) at 532 nanometer wavelength.

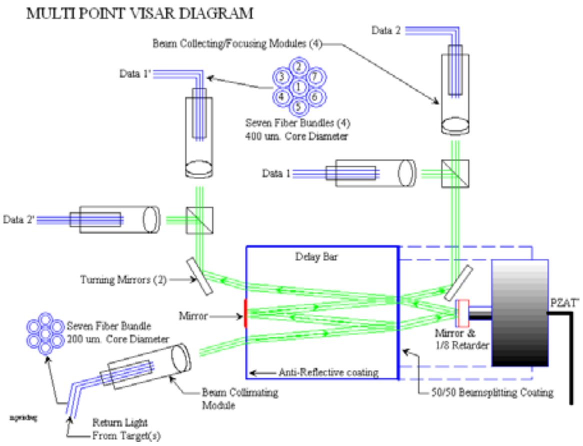

FIGURE. 1. LAYOUT OF THE MULTI POINT VISAR DEPICTING OPTICAL COMPONENTS AND BEAM PATHS

The VISAR cavity is a modified, unequal leg Michelson interferometer.[1] The components in the Fixed Cavity VISAR are cemented together to significantly reduce the need for alignment while greatly increasing optical stability.[2] This superior stability allows the user to trigger the recording equipment off the first motion of the event. The light from the output fiber optic, connected to the collimator, is routed through the cavity. The beamsplitting coating reflects one beam through the glass "delay bar" and the other beam through air and a 1/8 wave plate retarder. This waveplate effectively delays one component of the laser light by 90 degrees (The light passes through the 1/8 waveplate twice). This phase delay provides maximum data resolution for the sinusoidal waveforms that comprises the raw form of VISAR data. Since dv/dt at the peaks and troughs of a sine wave has minimal differences from point to point, discerning phase changes are difficult. Using the 90 degree phase delayed information with the reference (0 degree phase angle) information assures that maximum Δ*phase* is available at any time t during the measurement.

The beams are recombined to form two sets of interference patterns, which have simultaneous intensities 180 degrees out of phase with each other. This interfered light is routed to optical detectors, which convert the optical information to electronic signals. Half of the (180° out of phase) light is electronically inverted and added to the normal phase light which doubles the signal intensity and cancels out most of the self light that may have been generated during an experiment[3]. An (optional) bandpass filter placed in front of the return beam further filters the laser light to keep the signal-to-noise ratio high while excluding light generated from the explosive, or other photon-producing reaction.

Using VISAR to measure the results of a shock driven into, or through, a surface can be accomplished in two ways. The simplest measurement is of a "free surface". Laser light is directed onto a bare target and the reflected light is collected in a fiber optic that is routed to the interferometer cavity. When the surface is driven into motion, the Doppler shifted light from the surface is recorded, yielding a direct correlation of free surface velocity with respect to the Doppler shifted light. A second method commonly used to measure shock pressure is to prepare a transparent "window" material with a reflective coating on one side.[4] This window is attached to the sample with the reflective coating side adhered to the sample using a very thin adhesive layer. As the shock travels through the sample and into the window, a particle velocity is generated causing a Doppler shift in the laser light that is analyzed by VISAR diagnostics. If the shock Hugoniot is known for window and sample materials, the shock pressure of the sample can be derived from the particle velocity.

In an equal leg interferometer system, the Doppler shifted photon arrival time would be equal, resulting in no change in the interference pattern generated by laser light recombination. VISAR, however, has unequal length optical path distances in the interferometer cavity, resulting in different Doppler shifted arrival times at the beam recombination point**.** This path length difference is defined by:

$$\Delta\ length = (h(1-1/n))/\sin a \qquad (1)$$

where h is the delay leg length, n is the index of refraction in the delay etalon, and sin a is the correction factor for the angular path the beam travels through the cavity. The distance the light travels in the delay leg is longer than in the reference leg **and** the speed of light is slower in glass than in air. Using the relationship from equation (1), the delay time τ can be defined as:

$$\tau = \frac{2h}{c}(n-(1/n)) \qquad (2)$$

Where c is the speed of light in a vacuum and, in the latter term, n is the index-of-refraction of the optical elements.
Using these relationships, the fringe count $F(t)$ relates to target velocity $u(t-\tau/2)$ as:[5]

$$u(t-t/2) = \frac{\lambda F(t)}{2\tau(1+\Delta\nu/\nu)}\cdot\frac{1}{1+\delta} \qquad (3)$$

in which λ is the wavelength of the laser light, $\Delta\nu/\nu$ is an index of refraction correction factor for the window, if used, δ is a correction factor with respect to wavelength for dispersion in the etalon (delay bar) material. Equation (3) is manipulated to obtain the ***velocity-per-fringe*** (VPF) constant for an interferometer, which is:

$$VPF = \frac{\lambda}{2\tau(1+\Delta\upsilon/\nu)}\cdot\frac{1}{1+\delta} \qquad (4)$$

Data reduction software converts the sinusoidal traces to a polar plot, then to velocity, as a function of time, plot.

DATA REDUCTION

The Hugoniot of polymethylmethacrylate (PMMA) is the relationship between the shock and particle velocities of the material and is expressed as:

$$U_s = C_o + SU_p \qquad (5)$$

Where U_s is the shock velocity in mm/µs, C_o is the initial bulk sound velocity in mm/µs, S is a dimensionless empirical parameter, U_p is the particle velocity in mm/µs

For example, PMMA, from equation 5, has the form:

$$U_s = 2.49 + 1.69U_p \qquad (6)$$

The measured particle velocity can be plotted as a function of shock velocity. By knowing the values of shock velocity, particle velocity, and density, the compressive pressure can be calculated using conservation of momentum:

$$\mathrm{P} - \mathrm{P_o} = U_s U_p \rho_o \qquad (7)$$

Where P is the final pressure in GPa, P_o is the initial pressure, and ρ_o is the initial density in g/cc (in this case = 1.184).

MULTI POINT VISAR DESIGN

Having the ability to measure multiple zones of a surface, or surfaces, under shock loading makes modeling the device easier and more accurate. Previous methods for obtaining shock measurements from different areas of a device's surface were limited to either using several VISAR cavities, or measuring a different point on several similar units. Since the system can accurately measure several individual points of a target's surface simultaneously, the accuracy is greatly enhanced over previous methods.[6] Data reduction is performed identically to a single point VISAR, with the additional information of temporal correlation. The light gathering efficiency of the system is high, due to the use of the latest generation of low aberration, variable index-of-refraction optics. Using these optics with proper imaging design and fiber optic coupling, allows the measurement of multiple points, using only a single laser with moderate output power. MPV is a portable system due to the compact design and stability of the fixed cavity interferometer, and by using the latest developments in frequency doubled Nd:YVO lasers that operate on standard 120 VAC. The development of portable MPVs utilized the technology advances from VISAR designs used in underground experiments at the Nevada Test Site.[7]

OPTICAL DESIGN

Considerations for system design and development of the MPV are: mechanical stability, fiber-to-fiber coupling stability and efficiency, minimal aberrations, ease of fine adjustment, and accurate temporal correlation between measurement points **(FIGURE 2)**. Optical alignment components consist of five x-y-z translation stages specifically made for fiber optics which are used for fine adjustments. Polarizing beamsplitters and turning mirrors are integrally bonded and mounted to minimize area consumption and maximize rigidity of the optical system. The entire optical array is mounted on an internally vibration dampened optical breadboard that stabilizes the Multi Point VISAR, minimizing the need for adjustment.

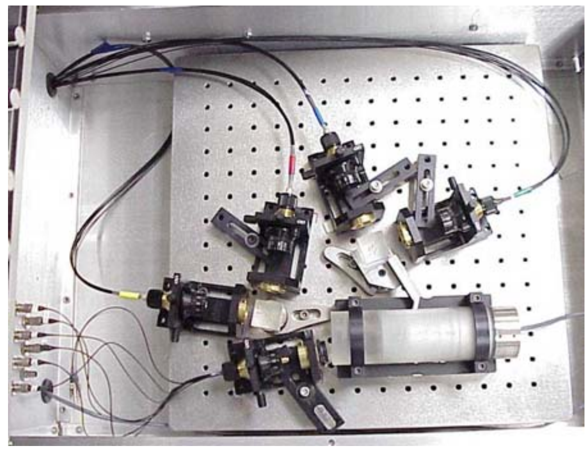

FIGURE 2. OVERHEAD VIEW OF THE MULTI POINT VISAR. THE OPTICAL BREADBOARD IS 16" SQUARE.

The safest and most versatile method for sending discreet optical information using the Multi Point VISAR is with fiber optic bundles. At first glance, one would infer that the diverging light emitted from a fiber optic would interfere with the light from the adjoining fibers in the bundle resulting in a scrambled optical signal. This scrambling is prevented by using multimode, incoherent fiber optics that avoid interference from adjoining fibers.[8] The role of the optics in the MPV cavity is to image an extended source (the emitting fiber bundle) through the system, then relay that image to the "receive" fiber optic bundles(**FIGURE. 3**) The optical relay system is designed to minimize aberrations while optimizing image magnification ratios. The laser light is focused into fiber optic beamsplitter(s), which are coupled to send/receive fiber probes that send light to the target(s), then collect the reflected light in one or more fiber optics.

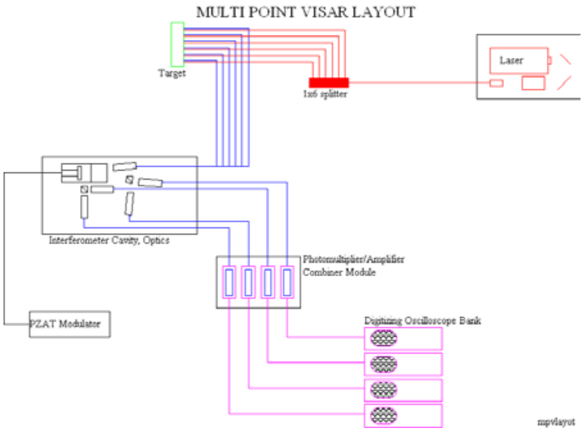

FIGURE. 3 MULTI POINT VISAR DIAGRAM DEPICTING A SIX CHANNEL SYSTEM

The Multi Point VISAR uses basically the same interferometer cavity as the single point fixed cavity system. The only modifications are the increased diameter of the reflective mirror on the delay bar, the combination mirror/waveplate assembly, and the turning mirror access slot. These modifications are needed to reflect and transmit the multiple beams, which emit light to form a larger image as it propagates through the optics. In this particular system magnification, is 2/1. The reason for the magnification requirement is that the diameter of the "send" fiber bundle is an approximation of the image of a single large fiber optic. That diameter is roughly equivalent to three times the diameter of a single fiber in the seven-fiber bundle. This results in a divergence angle through the interferometer cavity that is more than three times greater than that of a single fiber of the same diameter. The larger image diameter causes the beams to diverge as they propagate through the optical system, causing a larger image at the "receive" fiber optic bundles. If the send and receive fiber optics are of the same diameter and numerical aperture, and are used with a 1/1 magnification, the result will be an image with larger spherical aberrations, causing the outer six fiber optics in the bundles to exceed their numerical apertures (NA). This results in significant light loss and "cross talk" between individual fibers that potentially can corrupt the data.

OPTICAL TO ELECTRONIC CONVERSION

Traditional single point VISARs have four individual photomultiplier tube (PMT) detectors that convert the laser light to an electronic signal. These units are driven by individual high voltage power supplies that are varied to balance the gain of the detectors. The Multi Point VISAR uses high bandwidth-high gain 4 dynode photomultiplier tubes that currently have a 360 picosecond rise time **(FIGURE 4)**. The information is transferred from the photomultiplier tubes to 1.3 GHz bandwidth summing/inverting amplifiers, which add, invert, and amplify the signals

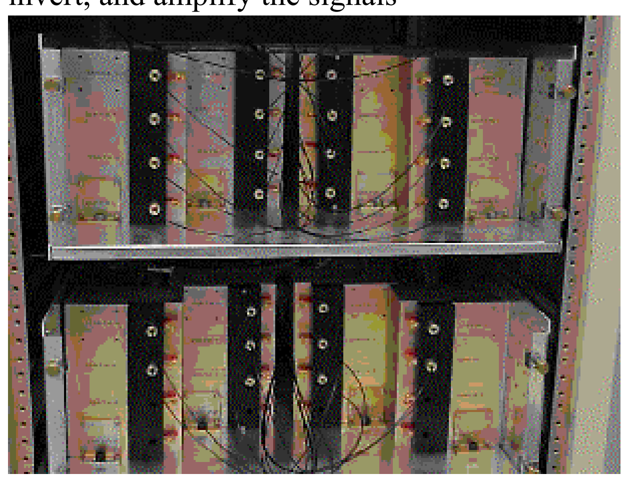

FIGURE 4. "FOUR POD" MODULES DISPLAYING A TOTAL OF 32 EMBEDDED PMT ASSEMBLIES.

Knowing the overall system accuracy (velocity-per-fringe constant), as well as temporal correlations between each channel is paramount in validating the accuracy of the Multi Point VISAR. Before attempting to quantify accuracy and maximum velocity measurement capability of a particular VISAR, the fill time void must be known. The fill time void is the temporal lag in the two (reference & delay) beams recombining to form interference fringes. This fill time is equal to the delay time τ. This fill time void is important in designing the appropriate system, in that some or most of the data in a fast event may be lost. Accuracy of a VISAR system, in general, is +/- 2% but this number may grow if the system is not optimized for the measurement event. It is desirable to minimize fill time and maximize the amount of fringes measured with a system without compromising the system bandwidth.

An important feature of Multi Point VISAR is its ability to measure temporal variations at multiple points.

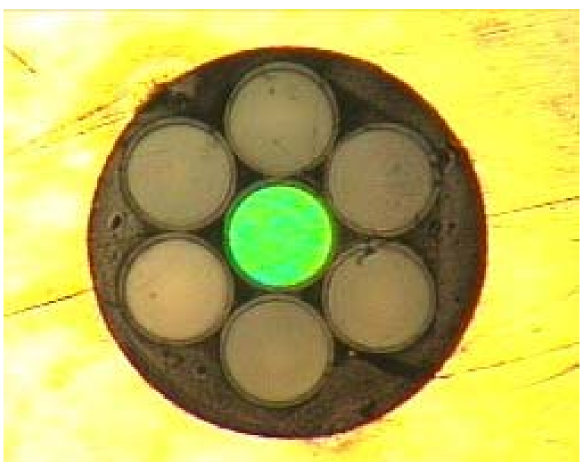

FIGURE 5. **PHOTOMICROGRAPH ILLUSTRATING THE CENTRAL ILLUMINATION FIBEROPTIC SURROUNDED BY THE "RECEIVE" FIBERS. EACH FIBER OPTIC IS 200 MICRON IN DIAMETER**

Since there are several components in a VISAR system that contribute temporal variations, the entire system must be calibrated to ensure the best accuracy. One method that affords simplicity, calibration accuracy, and is an indicator of absolute temporal resolution, is the attachment of a fiber optic bundle containing a central fiber optic that sends out laser light to a reflective target. This reflected light is collected by six fiber optics, which surround the "send" fiber optic **(FIGURE 5)**. This bundle is precisely fabricated to tightly surround the central fiber optic. This minimizes cosine errors due to the angular displacement of the central fiber output beam, to the six "receive" fibers. The reflecting surface is diffused to provide a uniform Lambertian light distribution which also minimizes cosine errors in the receive fiber optics.

The outgoing light is sent to a reflective surface that uses a detonator, or Detasheet, to produce a planar shock. The return (Doppler shifted) light is intercepted by the "receive" fibers where their light is routed to the Multi-Point VISAR. Since the reflected light is originating from a small target area, the Doppler shift should occur at almost exactly the same time for all the receive fiber optics. **FIGURE 6** displays a calibration shot using this technique. Each of the VISAR channels is recorded on similar equipment.

The calibration shot displays excellent simultaneity (**FIGURE 6)**. This technique is a powerful tool in determining the ultimate bandwidth of the system. Determining the bandwidth is accomplished by calibrating a system as shown above. Once temporal simultaneity is achieved, one of the fiber optic cables is incrementally shortened, then tested. When there is a perceived temporal difference, the same fiber is replaced with a longer one, until there is a perceived temporal difference. The two (long and short) fiber optic lengths are subtracted, then the time for light travel is calculated. This is the system limit for discerning shock arrival time. A typical fiber optic with a Numerical Aperture (NA) of 0.2 will have a throughput transmission time determined by the material, NA, dispersion, and to a small extent, the core diameter.

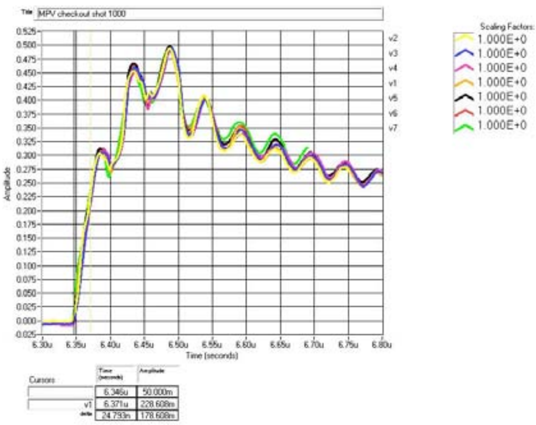

FIGURE 6. CALIBRATION TEST DISPLAYING SEVEN SEPARATE TRACES OVERLAID ON EACH OTHER. NOTE THE TEMPORAL ACCURACY OVER THE ENTIRE TIME-HISTORY OF THE EVENT.

There are a number of phenomena that contribute to the bandwidth limitations. Ultimately, these phenomena affect temporal accuracy and bandwidth of the VISAR. Although dispersion effects such as Rayleigh and stimulated Brillouin scattering contribute to temporal discrepancies, intermodal, or group delay has the largest effect on Doppler-shift resolution. Detailed discussion pertaining to ultimate bandwidth of a VISAR system is beyond the scope of this report, however, the following points are valid for maximizing the bandwidth of a system:

- Minimal fiber optic lengths
- (Typically) smaller core fiber optics
- Low fiber optic (NA)
- Mode mix incoming light into the fiber optic(s) as soon as possible
- Maximize the system velocity-per-fringe constant value (optimize data resolution)

It is important to note that Doppler interferometry (VISAR) bandwidth is (typically) significantly higher than digital bandwidth as advertised by fiber optic manufacturers.

EXAMPLE OF COLLECTED DATA

The following example of data collection illustrates the value of simultaneously measuring an event with multiple data channels of the Multi Point VISAR. The example illustrates a performance measurement of the pressure and planarity of an explosively driven device that is intended to deliver a planar shock wave to function other components **(FIGURE 7)**. Some of these devices are from systems that are decades old. Attempting to measure planarity using a single point VISAR is only possible by measuring one point, then initiating another device while measuring another point at a different location, assuming that all of the devices are functioning identically.

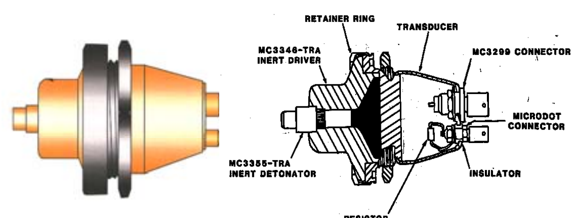

FIGURE 7. DRAWING OF ISOLATOR COMPONENT. DETONATION WAVE TRAVELS FROM LEFT TO RIGHT.

MPV is able to measure up to seven points simultaneously, which increased the amount of total data available by a factor of seven. In this example, the isolator (plane wave generator) has a detonator that initiates an explosive column that transfers a shock wave into a brass material. This material is bonded to 4340 chromoly steel plate, which is attached to a piezoelectric material. This piezoelectric component requires a planar shock wave to operate correctly. Until this component's performance was evaluated with Multi Point VISAR, there were no detailed multiple point shock planarity, or pressure measurements to validate the operation of the device. With such limited data, creating a validated model was impossible. **FIGURE 8** illustrates the detail of the shock-front at the exit face of the steel component as it passes into a PMMA window. An elastic wave precursor to the shock was believed to exist, although no accurate measurement methods existed (before VISAR) to validate the claim. The data in **FIGURE 8** illustrates the existence of the elastic wave, in addition to detailing the time-history of the shock propagation. In addition to the shock history, shock simultaneity was captured with a measurement error of +/- 4 nanoseconds

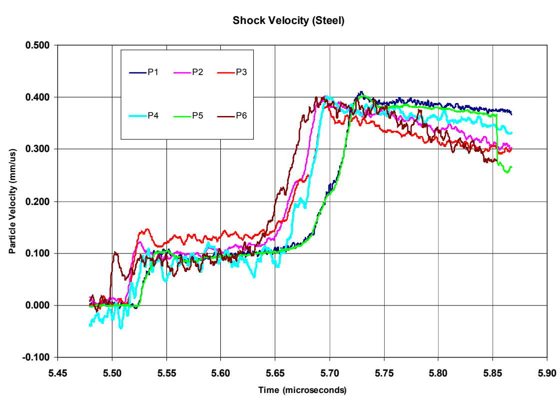

FIGURE 8. PARTICLE VELOCITY OF ISOLATOR SHOCK FRONT AT THE STEEL/PMMA INTERFACE (NOTE THE LOW PRESSURE ELASTIC WAVE PRECURSOR AT THE 5.52-5.65 TIME INTERVAL). SHOCK WAVEFRONT SIMULTANEITY IS +/- 20 NANOSECONDS

This data was used to plot shock planarity and shock pressure.

FIGURE 9 and **FIGURE 10**. depict the resultant shock arrival time and shock pressure at the brass/steel interface. The detail and recorded time history of the device provides useful information pertaining to the performance of these units during their lifetimes.

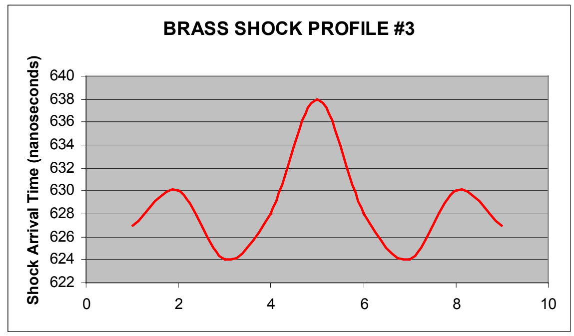

FIGURE 9. SHOCK ARRIVAL TIME PLOT FOR THE ISOLATOR COMPONENT'S BRASS/STEEL INTERFACE. THE TOTAL SHOCK ARRIVAL TIME DIFFERENCE IS 14 NANOSECONDS

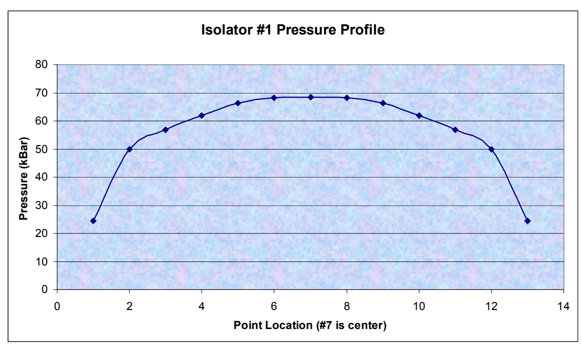

FIGURE 10. PRESSURE PROFILE OF THE SAME ISOLATOR. INTERFACE. PRESSURE DIFFERENCE IN THE USABLE AREA OF THE ISOLATOR IS 20 KBAR.

CONCLUSIONS

VISAR is now over three decades old, and there have been numerous improvements as ideas and technology mature. Multi-Point VISAR has added a new dimension to the classic single-point measurement technique. Additionally, the newer high-speed electronic instrumentation and the compact, high efficiency laser have made this system truly portable. This system is now capable of being powered entirely by a single mid-size generator, making remote field applications a realistic endeavor. A new Multi-Point VISAR has been designed which will contain 19 separate points in a single interferometer cavity. This system will be used for larger, or more detailed information suitable for validating and creating component performance models.

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A special acknowledgment goes to Lynn Barker, and Roy “Red” Hollenbach who substantially developed the VISAR to become a system that greatly enhanced the field of shock physics.

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