# FINAL REPORT

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Project Title: "A Quantitative Non-destructive Residual Stress Assessment Tool for Pipelines"

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## EXECUTIVE SUMMARY

G2MT successfully demonstrated the ***eStress***™ system, a powerful new nondestructive evaluation system for analyzing through-thickness residual stresses in mechanical damaged areas of steel pipelines. The ***eStress***™ system is designed to help pipeline operators find problem areas before serious damage occurs. High levels of tensile stress are the fundamental driver for dangerous corrosion and cracking in pipelines, which can be identified and mitigated proactively. The ***eStress***™ system, developed under DOT PHMSA SBIR Phase 1 and 2 funding, measures the pipe wall internal stresses within a damaged area, allowing operators to thoroughly inspect and analyze at-risk areas before failures occur. A key advantage of the ***eStress***™ system is that through wall stress measurements can be taken while a pipeline is in service, which allows direct measurement of the complex stress state of the dented materials under operating conditions. This is opposed to other methods that rely on a variety of assumptions, surface measurements and computational methods to arrive at stress estimates. The ***eStress***™ system uses an array of electromagnetic sensors to rapidly map out the stress in a pipe wall to analyze dents, bends, and other stress concentrators. The current 64- sensor array design can evaluate approximately one square foot in less than two minutes. It is also envisioned that the ***eStress***™ system could be installed permanently along high consequence areas or other areas of concern for monitoring the dynamic stresses that come from transportation, operation, pigging, nearby industry/citizens, etc.

The SBIR Phase 2 funding has enabled G2MT to advance the ***eStress***™ system from a lab scale proof of concept to a robust, portable, battery powered system suitable for field work. The SBIR funding has enabled G2MT to hire full time electrical and mechanical engineering talent required to develop and integrate the advanced software and hardware for the 64-sensor array system. Additionally, a 3D printing system was acquired to enable rapid prototyping of sensor housings that allow the articulation of the matrix array to conform to the surface of test materials such as dented pipe. The DOT SBIR has supported the growth of G2MT LLC from two to eight full time employees (and four part-time employees) and the first products to market are being prepared for the end of 2014. Additional spin-off technologies from this SBIR effort include a digital strain gauge system, high-temperature hydrogen attack analysis, and other proprietary efforts that are underway.

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## 1. BACKGROUND

G2MT, LLC has been at the forefront of developing advanced electromagnetic sensors to measure real-time through-thickness material properties that predict the integrity and safe operation of metal components. G2MT has developed the ***eStress***™ system to quantify through-thickness residual stress in operating pipelines exhibiting mechanical damage or re-rounding. Quantification of the residual stresses associated with a damaged region of steel pipeline provides a means to assess the severity of the damage, while reducing the amount of unnecessary removal and repair applications and enabling enhanced Risk-Based Inspection.

Under cyclic loading during pipeline service, mechanically damaged regions act as fatigue crack initiation sites. Crack initiation, which is the first stage of the appearance of fatigue cracking, becomes much easier to initiate in the presence of damage and defects because of the extreme local strain/stress fields around the flaw. The damage and associated residual stresses lower the overall fatigue strength of the steel and its weldments. Determining and detecting the limits of critical damage severity is essential to mitigating crack initiation and, therefore, mitigating fast crack propagation to failure.

Because mechanical damage, including dents, bends, wrinkles, and other forms, is the leading cause of all pipeline failures, it is essential to have a non-destructive means to measure the “true” residual stress of the pipeline at a specific moment in time compared to a calculated value using finite element analysis models. The finite element analysis models cannot calculate the “true” residual stress because the models ignore many variables that could locally increase the overall residual stresses beyond the tensile strength of the material. For example, most steel pipelines are cathodically protected, which means that hydrogen is continuously produced and the steel pipeline therefore has continuous exposure to atomic hydrogen, which prefers to migrate to high stress regions in the steel such as a mechanically damaged region or a weldment. When the hydrogen localized itself in the high stressed region, the presence of the hydrogen atom will continue to increase the total local residual stress, which ultimately lowers the stress necessary to failure. Knowing the “true” residual stress of the system via direct measurement will allow for much more accurate prediction of integrity, performance, and lifespan.

Steel pipelines with mechanical damage are currently assessed for integrity using standard pit gauges and geometric-based measurements. The standard pit gauge measures the maximum deflection and the deformation extent is then measured using a ruler or a straight edge. The severity of the mechanical damage of a bend, for example, is then calculated the wrinkle severity ratio, h/L (height/width), which is the geometric characteristic used to describe the severity of a given wrinkle [Alexander, C. and Kulkarni, 2008]. Integrity management programs charged with assessing wrinkles and bends consider the h/L ratio as the first-line grading tool [Alexander, C. and Kulkarni, 2008]. While geometric based measurements are useful as a gauge of the existing shape of the pipe, they do not provide information on the “true” stress or the actual “state” of the system and can lead to erroneous predictions for actual pipeline integrity.

A large body of research has been accumulated, particularly looking at stress-based and strain-based designs, corrosion analysis, FEA, and other characterization practices [PRCI, 2012; Phelps, 2012, Zarea, 2012]. Strain-based designs are currently popular because of the difficulty in measuring stress. Much of the prior research that focused on the ability to use strain-based design for high-strength steel has led to the conclusion that existing methods based on flow-stress of low-strength steels are not directly applicable. The effects of corrosion, toughness, and other material property changes have been noted to have substantial impacts over time on the integrity of pipelines but are not reflected in any current models.

A majority of regulations and codes are based on these models and other information with the intent of being conservative, but these assessment methods are not always effective in cases with complex geometries, re-rounding, or any of a host of other effects (such as hydrogen build-up) that can lead to localized regions of tensile stresses beyond the critical stress levels that are susceptible to cracking and failure. One of the most common complaints of pipeline operators is that, based on existing tests and codes, they remove or repair every indicated region yet the failures simply migrate to other areas. There is an immediate need for a new, quantitative method of assessing mechanical damage based on residual strain to enable operators to perform a more detailed in-field assessment of mechanical damage to determine damage severity.

Other NDE techniques, such as laser profilometry, x-ray, and ultrasound, have been evaluated for stress assessment but ultimately none provided repeatable and accurate readings. Profilometry, in particular, seems at first glance like a good possible fit but ultimately is entirely incapable of measuring internal effects such as stress, corrosion, cracking, etc. The Phase I research previously performed by G2MT demonstrated that the ***eStress***™ system is uniquely capable of evaluating these internal properties and providing a useful measurement of stress to compare with stress-based designs. The sensitivity to stress has been measured in pipelines of various ages, thickness, diameter, and grades, including welds. In the process of moving from laboratory to field-scale testing, G2MT has conquered many measurement challenges and has dramatically improved the technology.

## eStress System

G2MT measures the change in the stress in materials by measuring changes in the total energy of the system through variation in the electronic effective mass. To understand what the effective mass is, we start by assuming a nearly free electron model: the potential energy of a system is equal to zero and the electron's energy, E, is given as: $E = 1/2mv^2 = P^2/2m$, where m is the mass of an electron and v is the speed of the electron, P is the electron's momentum. With the deBroglie expression of the momentum given as $P = \hbar k$, then the electron's energy is expressed as $E = \hbar^2k^2/2m$, where m is the mass of an electron. When the situation occurs where there is a localized lattice potential interactions (the addition of some sort of strain from carbon, hydrogen, external load), the conduction electron's energy is modified to include the potential lattice interaction (strain) so the energy is now expressed as $E = \hbar^2k^2/2m + V$, where V is associated with the potential energy experienced by the conduction electron in the vicinity of the lattice atom. Now, a technique allowing the value of the mass of the electron to be altered to quantitatively incorporate the effect of V, the effective mass, $m_e$, is introduced to describe change in the electron's effective mass due to the strain as $E = \hbar^2k^2/2m_e$ [Wilkes, 1973]. In this manner, the nearly free electron formulation can be used to derive the electron properties of an alloy, thus making the effective mass a valuable parameter to assess the residual strain through electron property measurements.

The ***eStress***™ system directly measures the actual changes in lattice residual stress at specific points by measuring the change in electron momentum through the effective mass. When a metal is stressed, the conduction of the electrons is altered. The change in electron vibration can be directly correlated to a specific quantified residual stress using proper calibrations. Just like neutron diffraction, the ***eStress***™ system can monitor both the elastic and plastic strain/stress because the measurements are not dependent on the magnetic properties of the material, but dependent on the changes in electronic properties due to the lattice stress and strain. In reality, systems that cannot measure the total localized strain are insufficient for high-accuracy integrity management, because localized strain fields can quickly develop and become modified from continued external loading, presence of interstitial atoms (H, C, N, O) at interstitial sites, welding, etc, all of which further increase the lattice strain and modify localized strain energies.

During the DOT Phase 1 work, G2MT developed the unique ***eStress***™ system to three-dimensionally monitor residual stress (strain) levels associated with mechanical damage in steel pipelines. The ***eStress***™ technology provided a 3-D residual stress map of each region and then stores the data to compare with other regions to prioritize damage and determine subsequent repair or removal practices. G2MT's residual stress sensor technology provides a high-accuracy replacement for characterizing and prioritizing pipeline mechanical damage that can dramatically improve the effectiveness and value of pipeline damage testing to provide more realistic data for integrity management programs on the fundamental properties driving the formation and growth of cracks.

The G2MT ***eStress***™ technology was developed and tested on wrinkle bends (Figure 1) and dents with gouges through collaboration with El Paso Corporation, NIST-Boulder, and the NRC Canadian Neutron Beam Centre. The wrinkle bends are shown in Figure 1. All of these seven wrinkle bends in Figure 1 were four feet long with a five-inch wrinkle width and a 0.75-inch wrinkle height. This means that according to the, h/L, wrinkle bend severity all of the wrinkle bends are characterized as having the same severity. Residual stress measurements using the sensor in Figure 2 were performed along the length of each of the wrinkle bends to determine if there was a measurable difference in residual stress level changes between each of the wrinkles.

***Figure 1: Section of steel pipeline with wrinkle bends to be analyzed for residual stress levels.***

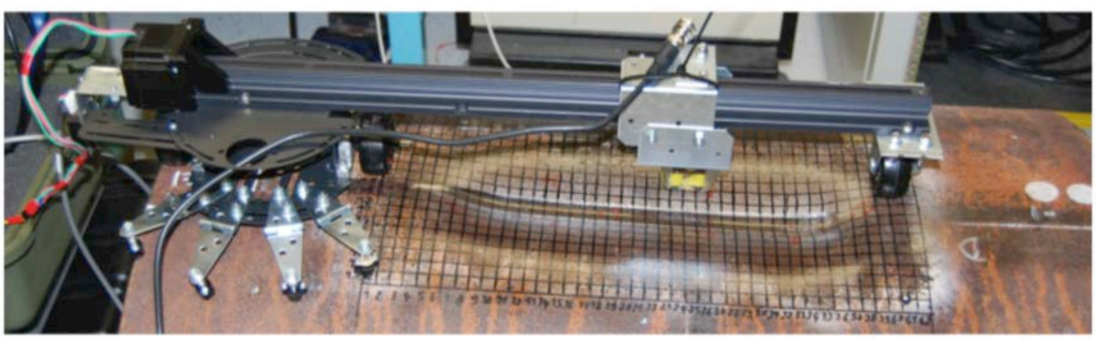

***Figure 2: Electromagnetic residual stress scanning probe for mechanically damaged pipeline steels.***

Figure 3 (a) is a residual stress contour map of wrinkle bend #5 at 0.191 mm beneath the surface as a function of the pipe circumferential direction and axial direction (Figure 3 (a)) and the residual stress profile as a function of depth down into the material towards the inner diameter (Figure 3 (b)). These results in Figure 3 show that there is a large variation in residual stress levels across the wrinkle bend into the undistorted region. Figure 4 shows the comparison of residual stress levels for all seven wrinkle bends shown in Figure 3 (at 0.191 mm beneath the surface) as a function of circumferential and axial directions. The comparison of residual stress profiles across seven different wrinkle bends (shown in Figure 1) indicate that the residual stress levels are largely variant across the wrinkles even though they have similar (measurably identical) geometries. All of the wrinkles exhibited significant measurable residual stress gradients through thickness and as a function of position across the pipe.

These differences in residual stress across wrinkles with similar dimensions shows the importance of having tools that measure the “actual” residual stress state of the pipeline at a particular moment in time. With continued operation, the residual stresses will change because of the cyclic operating pressures as well as hydrogen accumulation that occurs over time in cathodically protected pipelines. The G2MT ***eStress***™ technology proved to be successful in characterizing residual stresses across mechanically damaged pipeline steels. With the success in designing the ***eStress***™ system, G2MT was awarded the Phase II funding to develop the calibration system that will make the ***eStress***™ technology unmatched to all residual stress/strain technologies available to the pipeline industry today.

## 2. CHALLENGE

When a pipeline is mechanically damaged, both macro and micro-scale gradients of stress are established around the damaged area. Depending on the size, shape, extent of the damage, steel microstructure, defects, corrosion, and etc., these stresses vary in complex ways both around and through the thickness of the damaged region. The geometric-based methods currently used in the field can be replaced by much more useful and effective measurements based on residual stresses. By mapping and characterizing the residual stress around the entire region, any region above or near the critical residual stress can be indicated and the defined maintenance or integrity program performed.

The residual stresses associated with dents, bends, and wrinkles in steel form the basis for the nucleation and growth of cracks, especially at areas with the highest residual stresses. Quantified through-thickness residual stress characterization of dents, bends, and wrinkles provides a means to assess the severity of the damage through the coating while reducing the amount of unnecessary removal and repair applications, as regulated by Pipeline Safety Regulations 49 CFR Parts 190-195. Generation 2 Materials Technology, LLC (G2MT) has developed a quantified electromagnetic sensor to assess through-thickness residual stress in pipelines from the exterior and through coatings. Quantitative knowledge of the through-thickness residual stress level will enable enhanced Risk-Based Inspection and drastically improve pipeline integrity.

In Phase I, G2MT proved that the ***eStress***™ system could successfully measure through-thickness residual stress in mechanically damaged steel pipelines samples. For Phase II, G2MT has been challenged with calibrating the ***eStress***™ to measure through-thickness residual stresses in all existing and new pipelines of any strength, diameter, and wall-thickness.

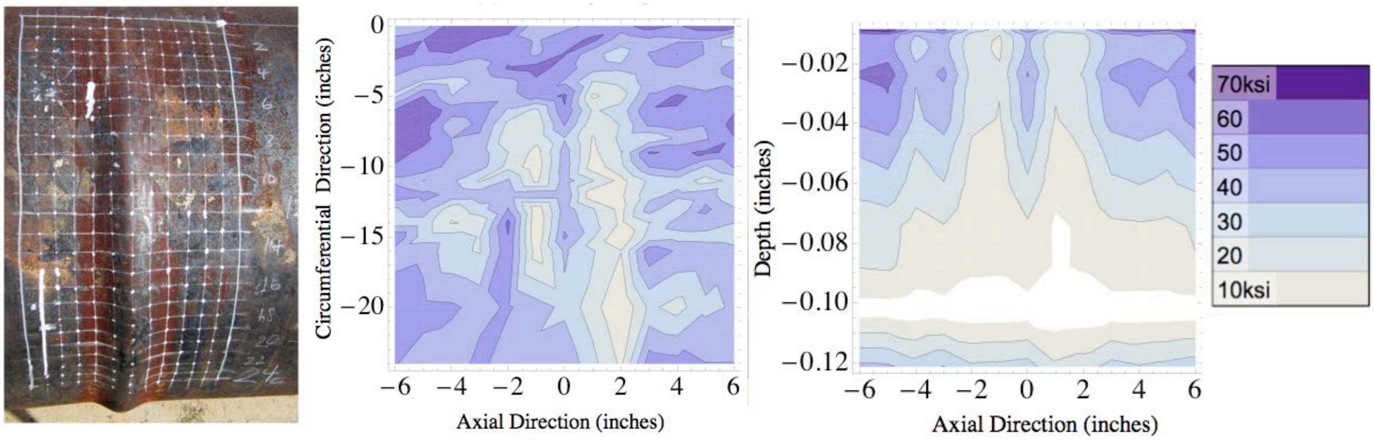


***Figure 3:  Residual stress contours as function of (a) circumferential direction and axial direction in a steel wrinkle bend (top view) and (b) depth and axial direction from a cross-section of the steel wrinkle bend (into the steel from outer diameter to inner diameter).***

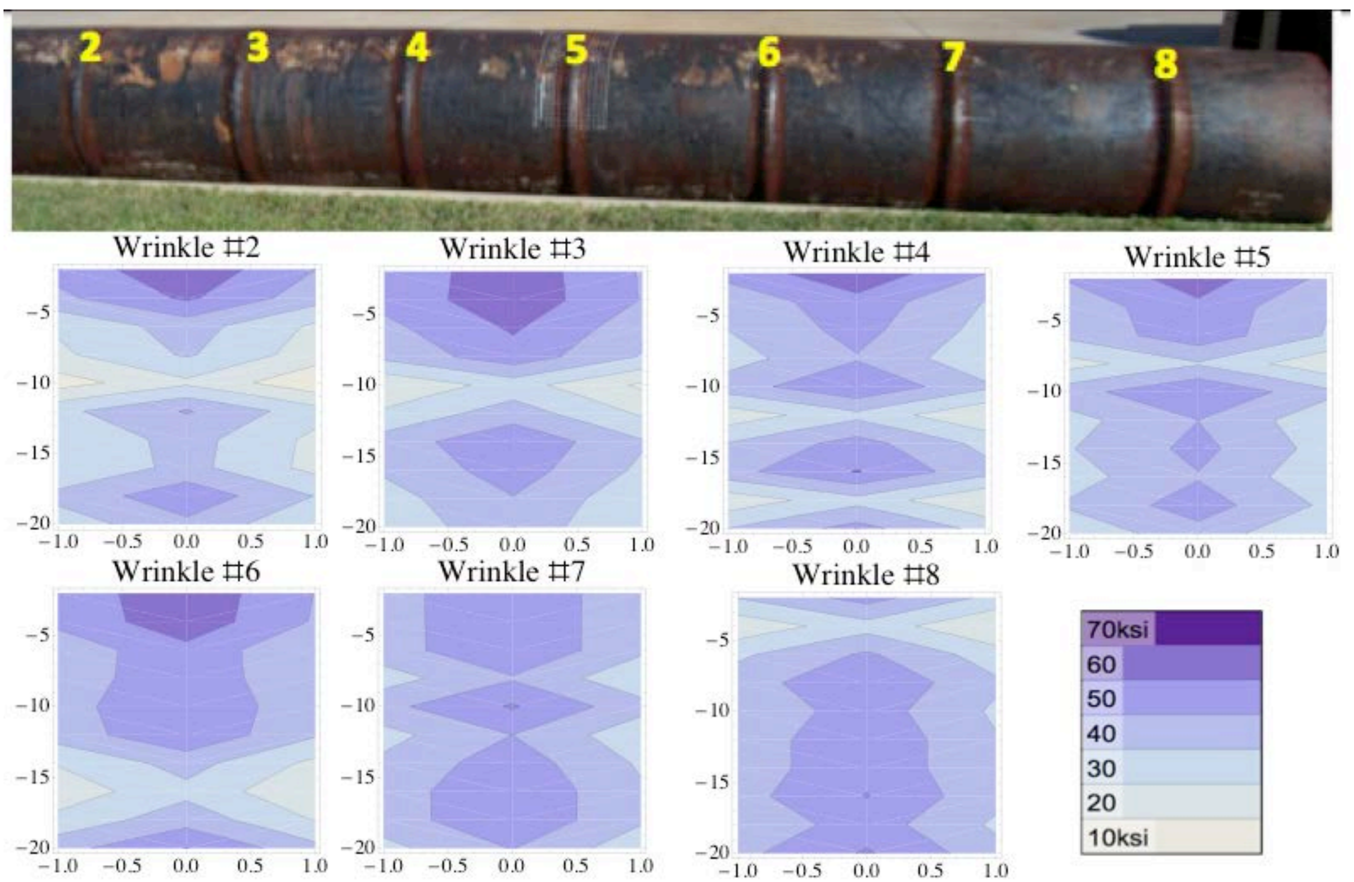


***Figure 4:  Top view of residual stress contours 0.191 mm below the surface as a function of circumferential and axial directions for the seven different steel wrinkle bends shown in the photograph.***

## 3. CHOSEN APPROACH

In Phase I, the G2MT ***eStress***™ system was designed as a single probe system with point-by-point measurements performed across a damaged region. To complete the ***eStress***™ system for commercialization, the challenges included: (1) updating the sensor to a floppy mat system that conforms to the damage and performs a full measurement of the entire region in less than two minutes, (2) full calibration of the floppy mat to allow for through-thickness residual stress measurements to be performed on all existing and new pipelines of any strength, diameter, and wall-thickness including damage in regions weldments, (3) determine the optimum data form to be most beneficial for the pipeline integrity management programs, (4) complete the packaging of the ***eStress***™system to a hardened, field read sensor, and (5) employ the ***eStress***™ floppy mat system in the field.

For efficiency, G2MT chose to approach all of the challenges simultaneously. The first floppy mat system was assembled, calibrated, and employed to gather information for improvements to the system especially in terms of durability and usefulness in the field. Over the two year period of this research, technology for the electromagnetic system as well as the floppy mat has continued to advance allowing the ***eStress***™ system to be updated dramatically. For example, the most current prototype of the ***eStress***™ system is being designed to be completely wireless whereas all the previous prototypes were not wireless. G2MT is working on commercialization of the latest version of the ***eStress***™ system and then will continue to improve later versions over time just like technology updates for computers and telephone.

To perform the calibration measurements, G2MT, LLC chose to work with pipe suppliers, machine shops, pipeline companies, and testing companies to collect samples and to perform the testing necessary for calibration and to obtain the most beneficial data for integrity management. To reduce the amount of time for the ***eStress***™ to gain popularity, the current ASME and API codes and standards were researched to determine how the residual stress data obtained from the ***eStress***™ measurements could be quickly and currently applied to already accepted codes and standards.

Throughout the Phase II two-year research period, G2MT employed the various ***eStress***™ prototypes in the field to optimize the durability and robustness of both the electromagnetic system and the floppy mat system. Even factors such as sunlight on the computer screen needed to be addressed for the most efficient use of the ***eStress***™ system. G2MT plans on commercializing the latest prototype of the ***eStress***™ system and introducing the final prototype to the market at the API 2015 Inspection Summit. With the success of the ***eStress***™ system, a “smart” crawler will also be considered to characterize an entire steel pipeline to find all regions of high stress including regions not visible with the naked eye.

## 4. OBJECTIVES

The primary objectives for the Phase II research was to make the ***eStress***™ system ready for commercialization for use on all pipelines currently operating in the United States. G2MT successfully completed the following the nine objectives to complete the development of the ***eStress***™ system: (1) Begin calibrations to develop ***eStress***™ system to quantify residual stress on any steel pipeline located in the United States. The pipeline steels can have yield strengths potentially ranging from 40 (past) to 120 ksi (future); (2) Calibrate the ***eStress***™ system to quantify the residual stress measurements; (3) Calibrate ***eStress***™ system for all other variables associated with steel pipelines to increase accuracy of ***eStress***™ system; (4) Calibrate ***eStress***™ system for lift-off variations due to coatings, corrosion product, user handling of sensors, etc.; (5) Complete the packaging of the ***eStress***™ system for the field; (6) Determination of optimum data form for integrity management program, (7) Complete training procedure and manual for the ***eStress***™ system; (8) Develop New Codes and Standards for Acceptable Residual Stress Levels in Mechanical Damage; and (9) Deploy the ***eStress***™ system in the field. The steps to determine and/or complete each objective and the subsequent tasks are further described in the following sections.

Objective 1: Begin calibrations to develop ***eStress***™ system to quantify residual stress on any steel pipeline located in the United States. The pipeline steels can have yield strengths potentially ranging from 40 (past) to 120 ksi (future).

To calibrate the ***eStress***™ system to quantify residual stress in any steel pipeline currently operating in the United States, it was necessary to understand the state of the current infrastructure as well as the plan for future pipelines yet to be installed. Once gathering a range of the types of the linepipe currently in the ground, G2MT gathered pipeline samples throughout the Houston area and beyond. The key was to obtain pipelines of varying vintage with a range of strength, diameter, and thickness. G2MT's subsidiary metallurgical laboratory, G2MT Laboratories, LLC, was fortunate to receive many pipeline failures (caused by mechanical damage and corrosion) for metallurgical failure analysis that were later used for development of the ***eStress***™ system. G2MT also developed a close relationship with Houston Metal Cutting allowing G2MT to obtain dozens of sections of new and used linepipe currently being used by industry. Having exposure to pipe that has been in and out of service is invaluable. Important calibration information is gained from both new and old pipe. All of the pipeline specimens received by G2MT were characterized for microstructure, chemistry, and tensile strength. The ***eStress***™ system was calibrated for variations in strength to allow for the ***eStress***™ system to be used on any pipeline grade.

G2MT also performed measurements at Battelle Memorial Institute on various linepipe specimens exhibiting mechanical damage. The damage was fully characterized in terms of size and type (X80 vs. X100), but were not metallurgically characterized, so the data from the linepipe was used as comparison and for statistical models used to calibrate the ***eStress***™ system.

Objective 2: Calibrate the ***eStress***™ system to quantify the residual stress measurements.

To calibrate the system appropriately for linepipe of various types and strengths, G2MT obtained a mechanical testing apparatus to be able to perform simultaneous mechanical testing and electromagnetic measurements to be able to run measurements on various grades of pipe at any moment. G2MT equipped all specimens with strain gauges to have a direct correlation between stress/strain and impedance as a function of linepipe strength. It is essential to have an understanding of how the stress/strain behavior changes between the grades of linepipe. For example, how does variations in the elastic modulus of a material modify the electromagnetic measurements? Those variations had to be determined and separated out using G2MT's proprietary variable separation techniques using advanced mathematics and solid-state physics concepts. The accuracy of the ***eStress***™ system is a step beyond the accuracy of strain gauges, because the ***eStress***™ system measures both elastic and plastic stress. Hydrogen atoms always localize in regions with high tensile stress and the presence of the hydrogen atom continues to increase the tensile stresses. Accuracy from ***eStress***™ also extends beyond the accuracy of mathematical computer models which can not accurately account for unforeseen variables that will have a drastic effect on residual stress values, such as the presence of hydrogen atoms.

Objective 3: Calibrate ***eStress***™ system for all other variables associated with steel pipelines to increase accuracy of ***eStress***™ system

To calibrate the ***eStress***™ system for all other variables associated with steel pipelines, G2MT performed calibration measurements to account for variations in pipeline such as temperature, operating pressures, magnetic remanence (from "smart pigging" applications), cracks and pits on internal and external surface of pipeline, and other variables to eliminate the chance for any unexpected anomalies in the results. The ***eStress***™ system is based off of electronic measurements which are sensitive to many variables such as temperature and magnetic remanence. The affect of each of these variables is determined on the measurements and their affect is accounted for in G2MT proprietary mathematical algorithm. This means that the ***eStress***™ system can successfully be utilized on a pipeline in most typical operating environments in the winter time or the summer time because variables such as temperature are no longer viable factors in affecting the accuracy of the residual stress measurements. G2MT performed measurements on pipelines located throughout Texas at various periods throughout the year to check the accuracy of the algorithms accounting for the many variables. Because the residual stress calculated by mathematical models is insufficient to compare to the actual residual stress determined from the ***eStress***™ system (as shown in Phase 1 testing of identical wrinkles), G2MT is performing burst tests to determine the accuracy of the ***eStress***™ system by using the ***eStress***™ system to predict the burst pressure before testing.

Objective 4: Calibrate ***eStress***™ system for lift-off variations due to coatings, corrosion product, user handling of sensors, etc.

G2MT had to perform a calibrations to account for variations in lift-off (distance between sensor and steel surface) for any reason that could cause the ***eStress***™ sensor to not be within a specific distance away from the steel surface. The lift-off difference was established by using air and various other materials as the medium between the sensor and the steel pipeline. After establishing the effect of liftoff on the electromagnetic measurements, G2MT modified the original algorithm to account for the variations in lift-off. Understanding the effects of changing lift-off is very important because the lift-off dramatically alters the electromagnetic signal. All of the variables determined and measured in Objectives 3 and 4 were incorporated into the proprietary algorithm for the ***eStress***™ system to accurately measure residual stress in pipelines of any grade and vintage.

Objective 5: Complete the packaging of the ***eStress***™ system for the field.

The goal was to make the ***eStress***™ system robust and lightweight for field use. The system was developed from a fragile lab-based combination of multiple electronic components into a backpack or briefcase-sized real-time handheld sensor with a digital touch screen. To facilitate extended use in remote locations, the ***eStress***™ system now incorporates a wireless operating unit using satellites or cellular towers to immediately transmit data to the appropriate integrity management source. The reality was that a single-probe handheld sensor would take too long to perform measurements, so G2MT modified the original plan and made a series of full-scale floppy mat systems with variation configurations from 3x2 (3 rows of 2 each) to a 15 x 15 grid for rapid measurements of large areas. The floppy mat system is designed with proprietary linkages designed to allow a sturdy but flexible arrangement of the probes. The mat can be conformed to the damaged region on pipes of many different sizes to analyze the through-thickness residual stress of the full damaged region all at one time versus a point by point measurement scheme using a grid.

G2MT also knew that it was important to bring in outside expertise to complete packaging and prepare for commercialization and manufacturing appropriately. G2MT hired the services of Optimation, a company that offers industrial and manufacturing engineering services and full service automation solutions, to help with data optimization, increasing the number of measurable channels

(60 single sensors running simultaneously on mat sensor), sensor packaging, and manufacturing. Optimation has the unique ability to provide complete engineering, automation, construction and maintenance services, from the conceptual stage, through prototyping, all the way to full production-scale operations. Optimation's multidiscipline engineers, designers, and skilled tradespeople work together to successfully deliver thousands of projects each year throughout the world. Optimation is a licensed partner of National Instruments, who also provides software to G2MT for the ***eStress***™ system. After two years of working with the engineers and scientists from Optimation, we have since made one engineer a full-time G2MT employee and two scientists part time G2MT employees. The value the Optimation engineers brought to G2MT was priceless.

Objective 6: Determination of optimum data form for integrity management program

To determine the optimum data form output from the ***eStress***™ system, G2MT contacted pipeline owners and pipeline integrity management teams to determine what programs are currently in place or what programs should be in place. G2MT learned that the most important factor is the type of residual stress that is measured. An operating pipeline experiences hoop, longitudinal, and radial stresses. The ***eStress***™ system measures a single residual stress value and was not designed to measure three different types of residual stresses (which is not to say that the system could not be properly calibrated to distinguish between the different stresses but that was outside of the scope of this work). The ***eStress***™ system is designed to measure the total residual stress present in the system at a specific point (point located under each individual sensor), so it includes the sum of the hoop, longitudinal, and radial stresses. The accuracy of the residual stress predicted by the ***eStress***™ system has been determined and reproduced many times using tensile and 4-point bend test systems, and the ability to use residual stress analysis to verify pipeline integrity will best be verified through burst testing, which will be conducted through the remainder of the year in collaboration with Tejas Engineering. G2MT continues to optimize the data retrieval and analysis process and will soon move completely to a secure, fast, and easily accessible system that utilizes cloud computing (essentially allowing us to perform analysis that takes days on a single computer in a fraction of second by using banks of 1,000's of cloud-linked computers) and storage.

Objective 7: Complete training procedure and manual for the ***eStress***™ system

G2MT developed the operating manual and training procedures for the operation of the ***eStress***™ system using the new large floppy mat. G2MT worked with pipeline inspectors to develop an easy, user-friendly manual and training system. The manual and training procedure will be published and available to the public when the commercialized product is officially on the market. The current version of the operating manual is shown in Appendix A. Additional final details, screen shots, photography, and other modifications will be included with the final version of the manual.

Objective 8: Develop New Codes and Standards for Acceptable Residual Stress Levels in Mechanical Damage

ASME has current regulations (ASME B31.4 and B31.8) for stress/strain limitations on oil and gas pipelines. However, when damage occurs, it is unclear with current methods whether or not these stresses have been exceeded, leading to the use of ASME B31G, RSTRENG, and similar evaluation methods based on the thickness of the pipeline and extent of corrosion damage (by depth). These techniques are insufficient in many applications, such as (1) high-strength pipelines, (2) areas of hydrogen accumulation and embrittlement, (3) re-rounding of dents, etc, because they are only based on the thickness and yield strength of the material. As an alternative, the **eStress ™** system allows direct measurement of the localized stress to be compared against the ASME guidelines.

The allowable stress levels in hazardous liquid pipelines and gas pipelines are set in ASME B31.4 and B31.8. According to ASME B31.4, the allowable stress for hazardous liquid pipelines is set at:

$$S = 0.72 S_Y E \quad [1]$$

where 0.72 is a design factor, E is the longitudinal weld joint factor, and $S_Y$ is the specified minimum yield strength. While the allowable stress for gas pipelines according to ASME B31.8 is set at:

$$S = S_Y FET \quad [2]$$

where F is a design factor, E is a weld joint factor, and T is temperature de-rating factor. These equations and the appropriate constants will be input into the G2MT system to be used to categorize the damaged regions on pipeline as acceptable or unacceptable based on whether or not the measured residual stress is within the allowable stress limits for hazardous liquid and gas pipelines. ASME B31.4 and B31.8 were last updated in 2012. Having the ***eStress***™ system based on improvements of current codes and standards versus having to develop new standards will hopefully help the ***eStress***™ system gain acceptance more rapidly.

Objective 9: Deploy the ***eStress***™ system in the field

G2MT has employed the ***eStress***™ system in the field throughout the development of the floppy mat system for the sake of making sure that the system would work as designed and to determine how the system would age with continued use. G2MT is conveniently located in Houston where there are many exposed pipelines in accessible places allowing the opportunity for field measurements to be made at any time. G2MT has also worked on and performed many failures on damaged and corroded pipelines for various major pipeline companies that allowed G2MT to perform measurements on actual damaged pipelines that were in service. G2MT is and will continue to piggyback on existing NDE inspections of pipe when they are available. The publicity of the ***eStress***™ system on the DOT-PHMSA website has gotten G2MT noticed by companies around the world in various industries. We have also had chemical, recycling, and chemical storage plants open their doors fully to allowing G2MT access to utilize our sensors in their plants during downtime to measure residual stresses in various components including pressure vessels and piping. Most of the industries seem so desperate for new solutions that they are very willing to try anything that could provide them more information about the integrity of their plants.

## 5. RESULTS

G2MT has spent the last two years preparing the ***eStress***™ system for commercialization. G2MT had a long road ahead to commercialization and manufacturing which included: (1) improving the internals of the electromagnetic system and completing final packaging design, (2) improving the floppy mat system to ensure it will reliably provide fast, efficient, and reliable data that is accepted by industry during long-term use, and (3) developing the software to interface the user with the ***eStress***™ system. The internals of the original electromagnetic hardware appeared pretty rough early on in Phase II as shown in Figure 5, however the internals were in the process of being remanufactured to belong solely and exclusively to G2MT. By the end of 2013 (beginning of Phase II), G2MT had made its own printable circuit board to run the ***eStress***™ system as partially shown (to protect IP) in Figure 6. G2MT has continued to modify the circuitry as technology advanced in the past two years including always trying to make the system more compact.

The first prototype of the floppy mat was a package of multiple sensors in one system where each sensor performed simultaneous residual stress measurements at their respective locations. The first proto-type of the floppy mat is shown in Figure 7. This particular mat consisted of a six-sensor arrangement configured inside of Dragonskin plastic. This mat system was important because it immediately made us aware of the variables associated with electromagnetic sensors located within a specific distance from another sensor. G2MT wanted to improve the manufacturing process of the floppy mat system as well, so a 3D printer system was used to print out our mats. The designs for the original printable mats are shown in Figure 8.

Each sensor is interconnected but allowed to move freely to conform to the damaged pipe. The number of sensors can be increased or decreased at any time just be assembling or disassembling the plastic components. The plastic components and sensors are still contained inside of a plastic material to protect the sensors and to conceal their internals. The sensors will be intentionally destroyed if they are removed from the plastic to protect G2MT's intellectual property. The actual printed floppy mat system with 225 sensors is shown in Figure 9 before being mounted in plastic and afterwards in Figure 10. Notice how it nicely conforms to the damage on the pipe in Figure 9. The more the mat conforms to the pipe, the less lift-off and more powerful the signal.

During the development of the ***eStress***™ system for commercialization, G2MT tried to utilize methods that allowed for the most simplistic reproducibility methods that optimize the manufacturing process such as printable map sensors and printable circuit boards. The latest version of the ***eStress***™ system is shown in Figure 11. The ***eStress***™ system user interface and software are just as important as the hardware. For the first generation of the ***eStress***™ system ready for commercial sale in early 2015, the residual stress data will be displayed on the screen and will show whether the inspected region passes or fails the inspection based on the allowable stress limitations in ASME B31.4 and B31.8. The regions that fail show up as red and the regions that are acceptable remain green. Numerous versions were examined to determine the optimum way to display the data so that the operator could easily see the data from multiple perspectives without requiring training on how to use the program. The user interface is very user friendly and consists of basically telling the instrumentation when to start gathering the data; then the answer is immediately displayed for the user to make a decision of whether to repair or replace the pipe.

The next generation of the ***eStress***™ system (projected to be ready by the end of 2015) will include the full data analysis that will be automatically sent to the RBI and FFS modelers for risk and life prediction models. Examples of the original software development are shown in Figures 12 through 14. Then, when put into action it appears as shown in Figures 15 and 16. Note that a different version of the floppy mat system is shown in Figure 15. Multiple versions were made to deal with stiffness of the floppy mat to make sure that the system would still conform to the pipe after the wiring of the sensors was complete.

Figure 16 shows the actual screen that the user will interface when in the field. The screen shows three different measurements performed next to one another (by picking up and moving the mat) and the data was then automatically stitched together by the program. The user would note the regions that show up red as regions that need to be repaired or replaced, the yellow regions should be monitored in the future, and the green regions are completely acceptable and do not require repair or replacement. Notice on the screen the main buttons the user must interface with are the "read baseline" and "read mat" measurements. The baseline measurement is performed on the pipeline sample in an undamaged region next to the damaged region and the "read mat" measurement is used when performing measurements on the damaged region, which is described in the manual. The user can choose between the methods of visualizing the data similar to the variations shown in Figures 12 through 14.

G2MT was trying to determine the best way to display 3D data that can be sliced at any x, y, or z position to understand the residual stress distribution. The computer on the ***eStress***™ system is operated using touch screen and/or an attachable/detachable keypad. Once the “read mat” button is pressed, the full residual stress measurement takes approximately two minutes and then the resulting residual stresses will be displayed as shown in Figure 16. A video of the ***eStress***™ system in action is shown at www.g2mt.com.

The final ***eStress***™ system will be patented for use in pipeline applications and is in the beginning stages of the patent process. The components and the algorithms of the ***eStress***™ system will not be patented but will always remain a trade secret to protect the ***eStress***™ system as well as future sensors also currently under development at G2MT.

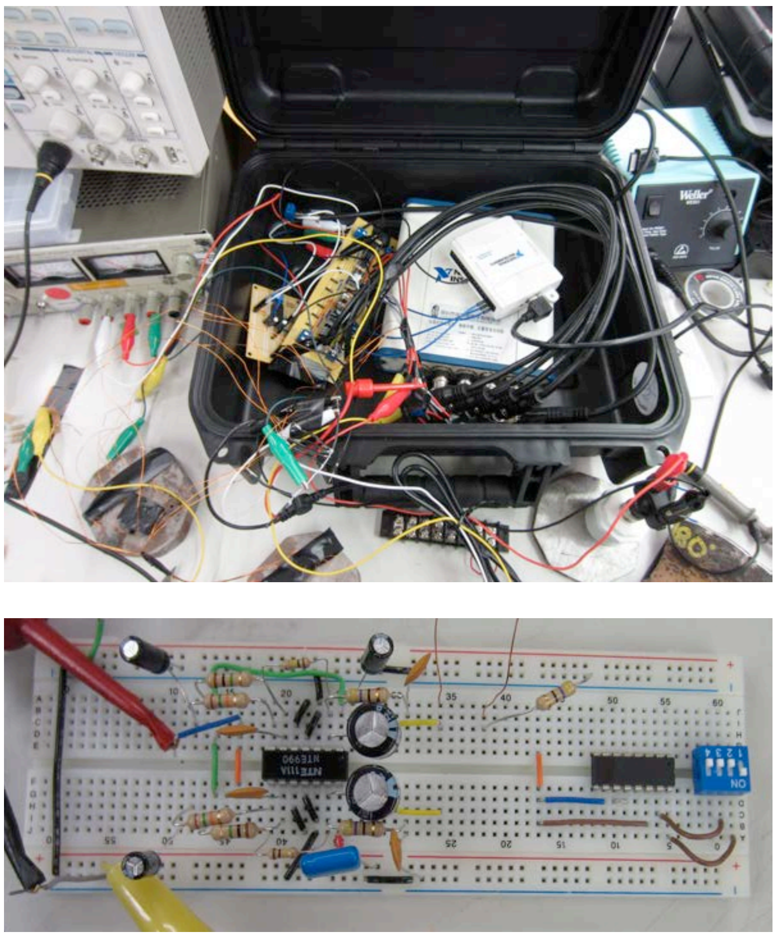

***Figure 5: Photograph of the internals when the project initiated.***


***Figure 6: Photograph of the proprietary G2MT circuitry for the eStress™ system.***

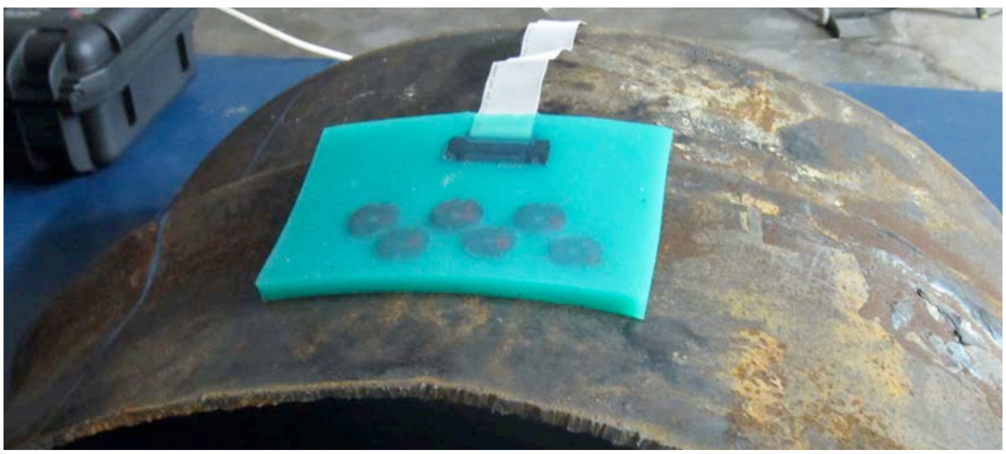

***Figure 7: Photograph of the first prototype of the floppy mat system for damaged pipelines.***

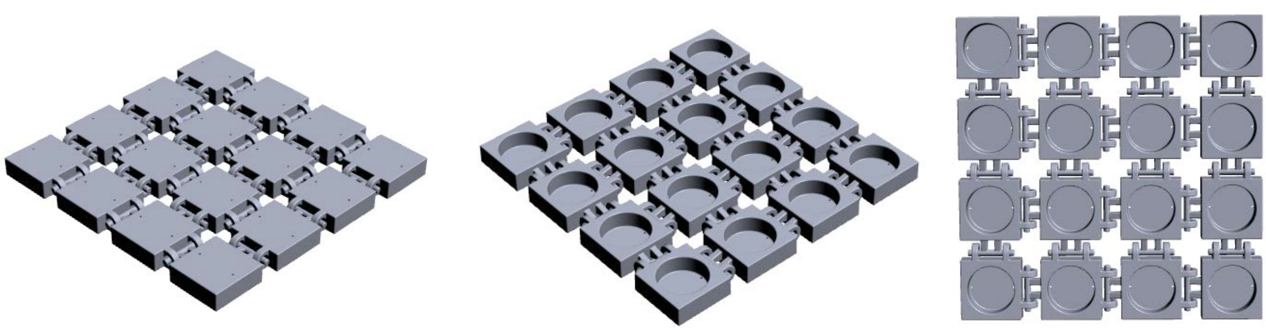

***Figure 8: Original designs of the components for the floppy mat system made with the 3D printer.***

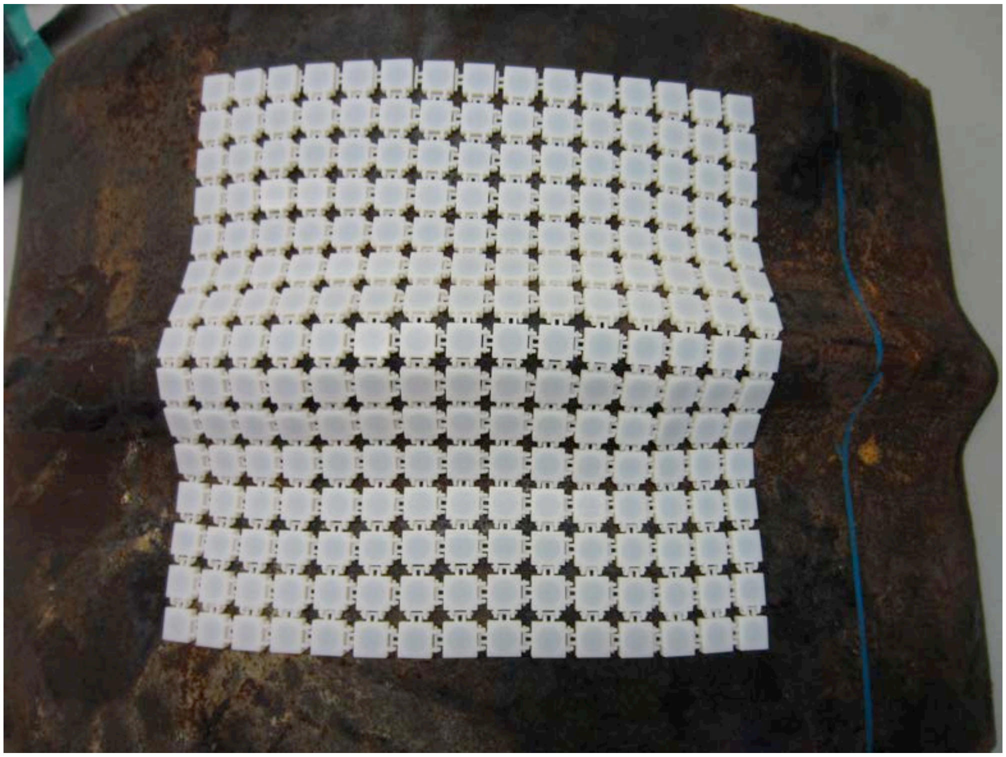

***Figure 9:  Photograph of the printed floppy mat system with 225 sensors.***

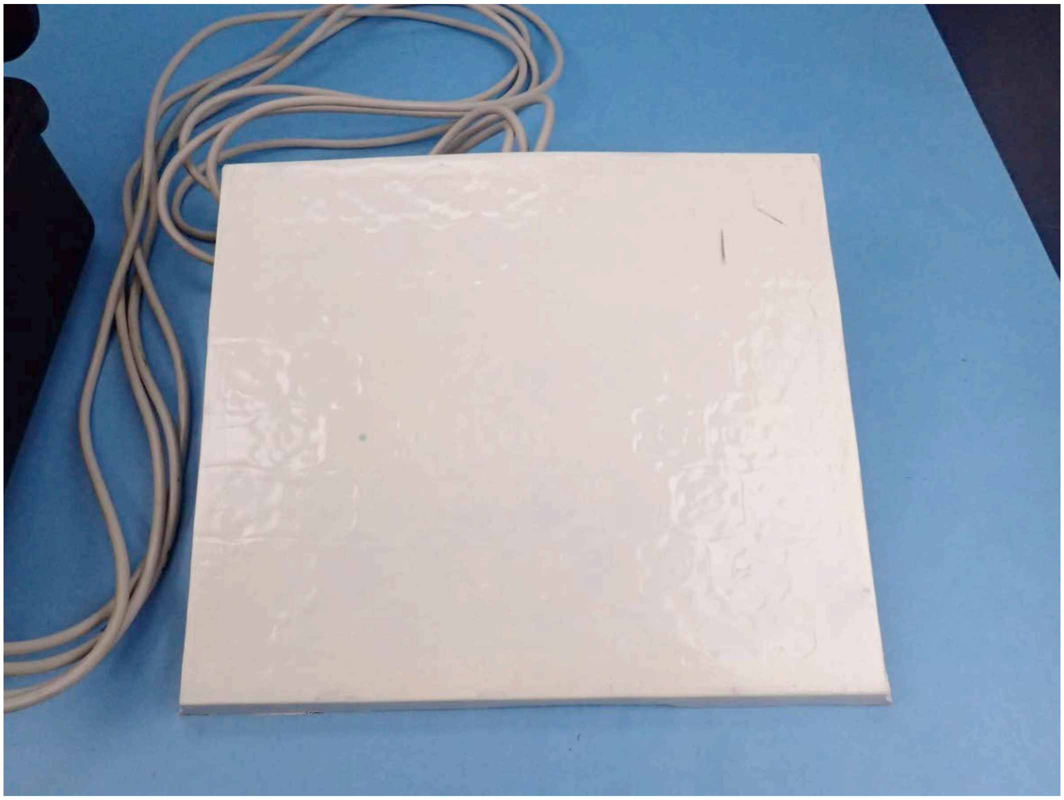

***Figure 10:  Photograph of the floppy mat system after being coated with plastic.***

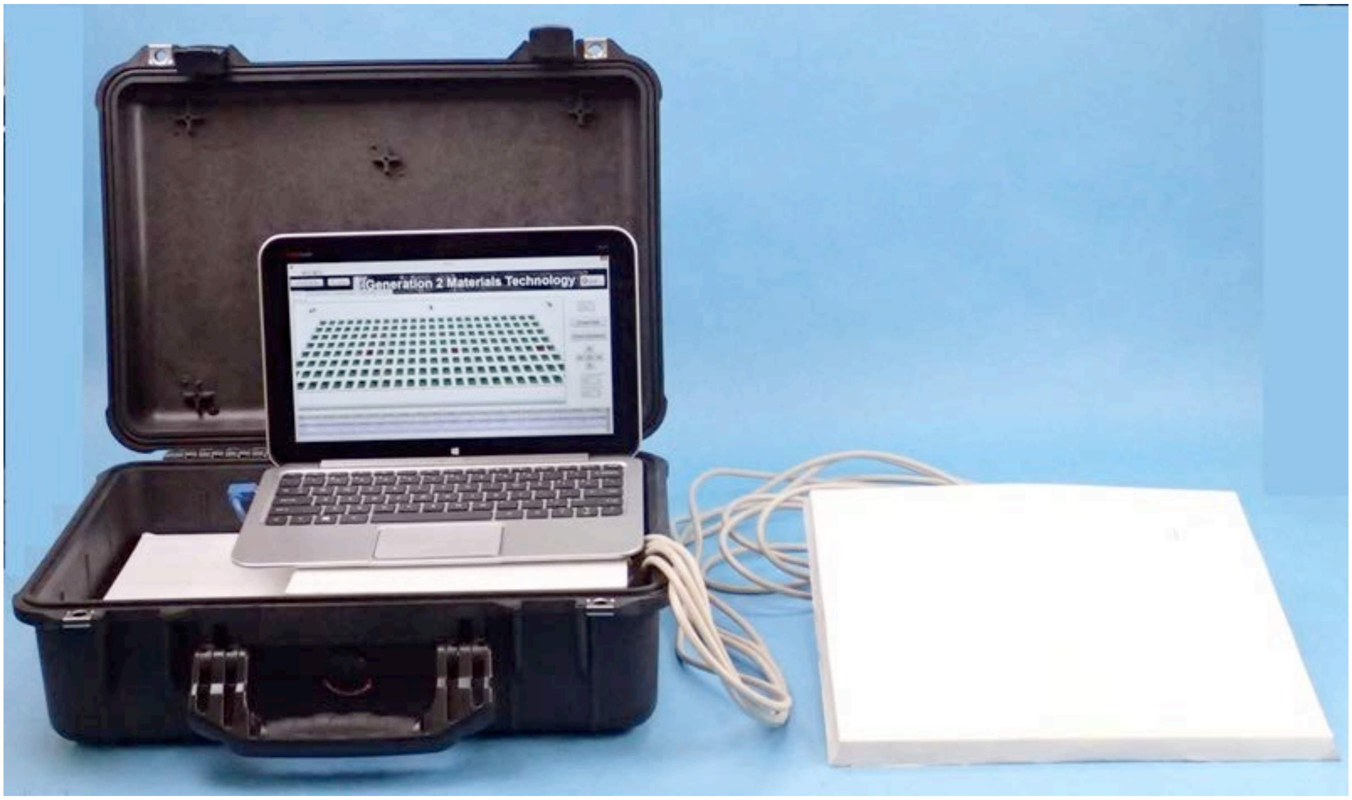


***Figure 11: Latest prototype of the eStress™ system from September 2014.***

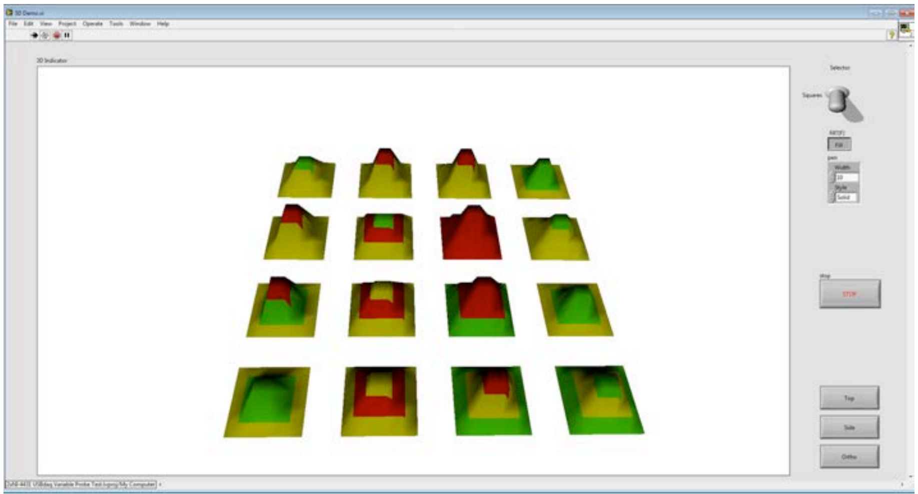

***Figure 12:  Screenshot of the top and side 3D view of the eStress™ system software data showing regions measured by the sensors that are acceptable versus unacceptable.***

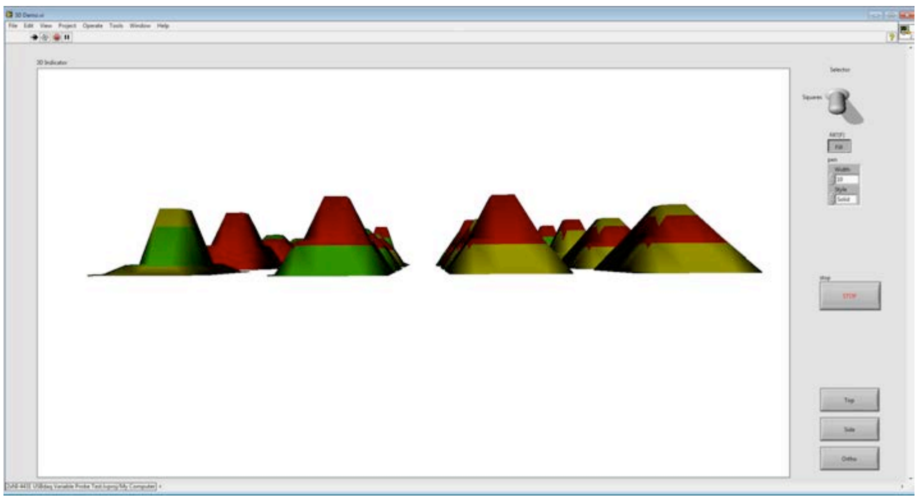

***Figure 13:  Screenshot of side 3D view of the eStress™ system software data showing regions measured by the sensors that are acceptable versus unacceptable.***

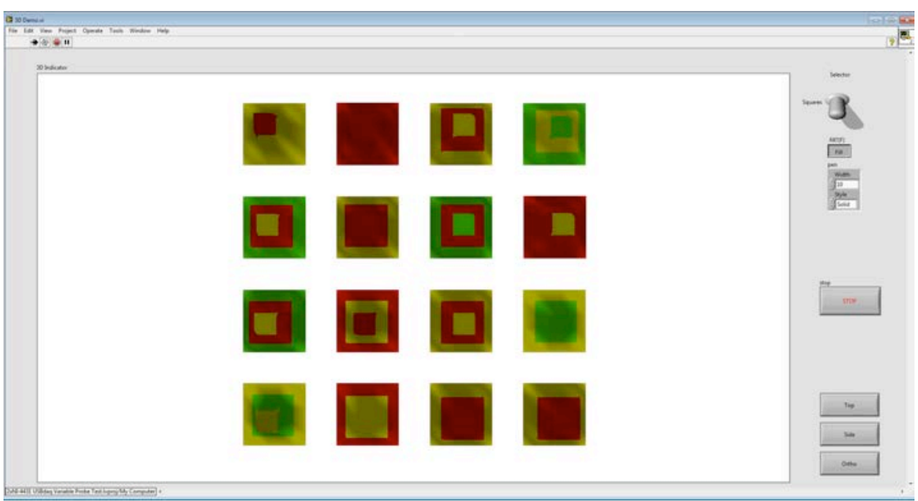

***Figure 14:  Screenshot of the top view of the eStress™ system software data showing regions measured by the sensors that are acceptable versus unacceptable.***

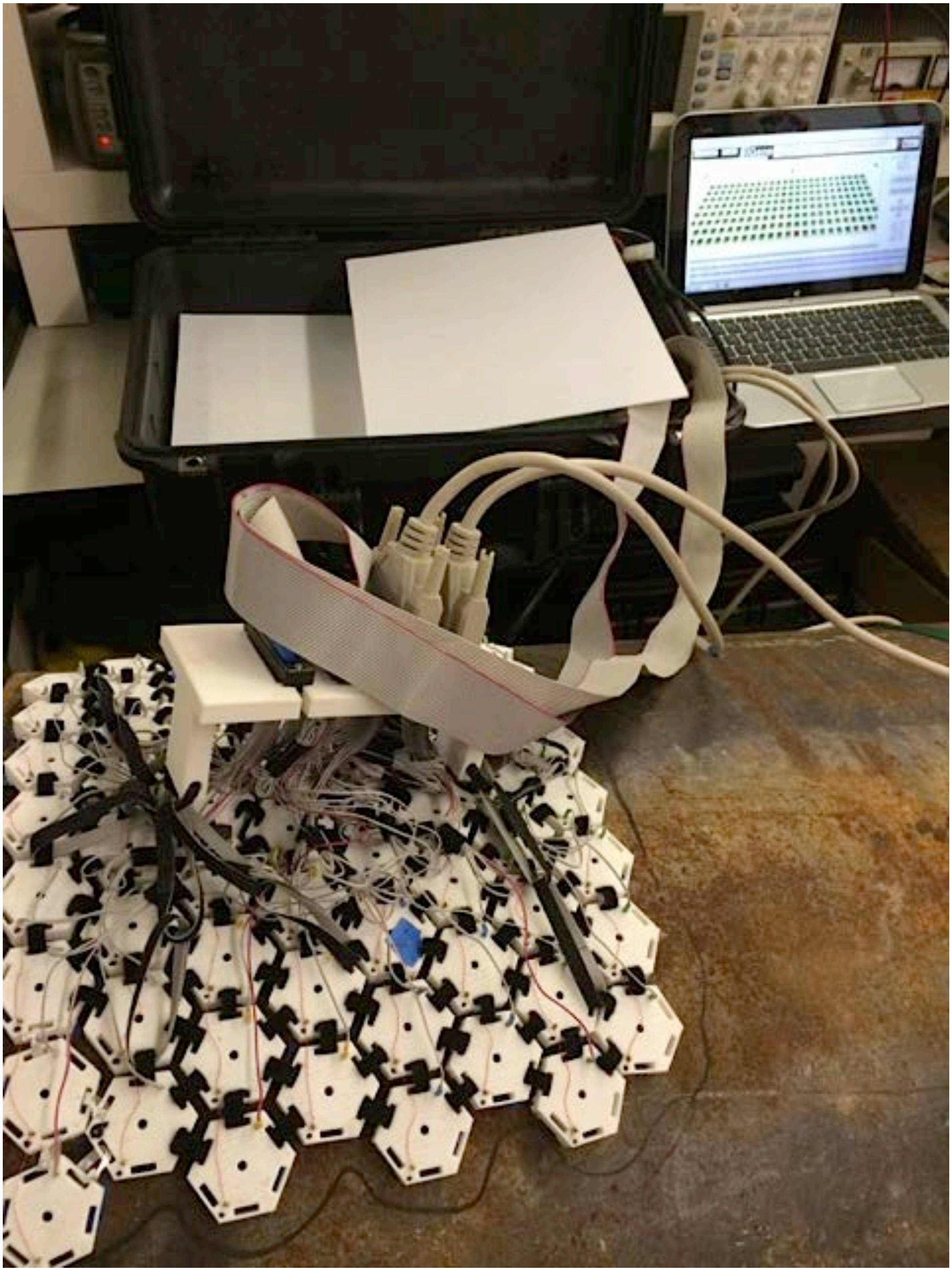

***Figure 15:  Photograph of the floppy mat system being run by the G2MT eStress™ system program shown on the computer screen.***

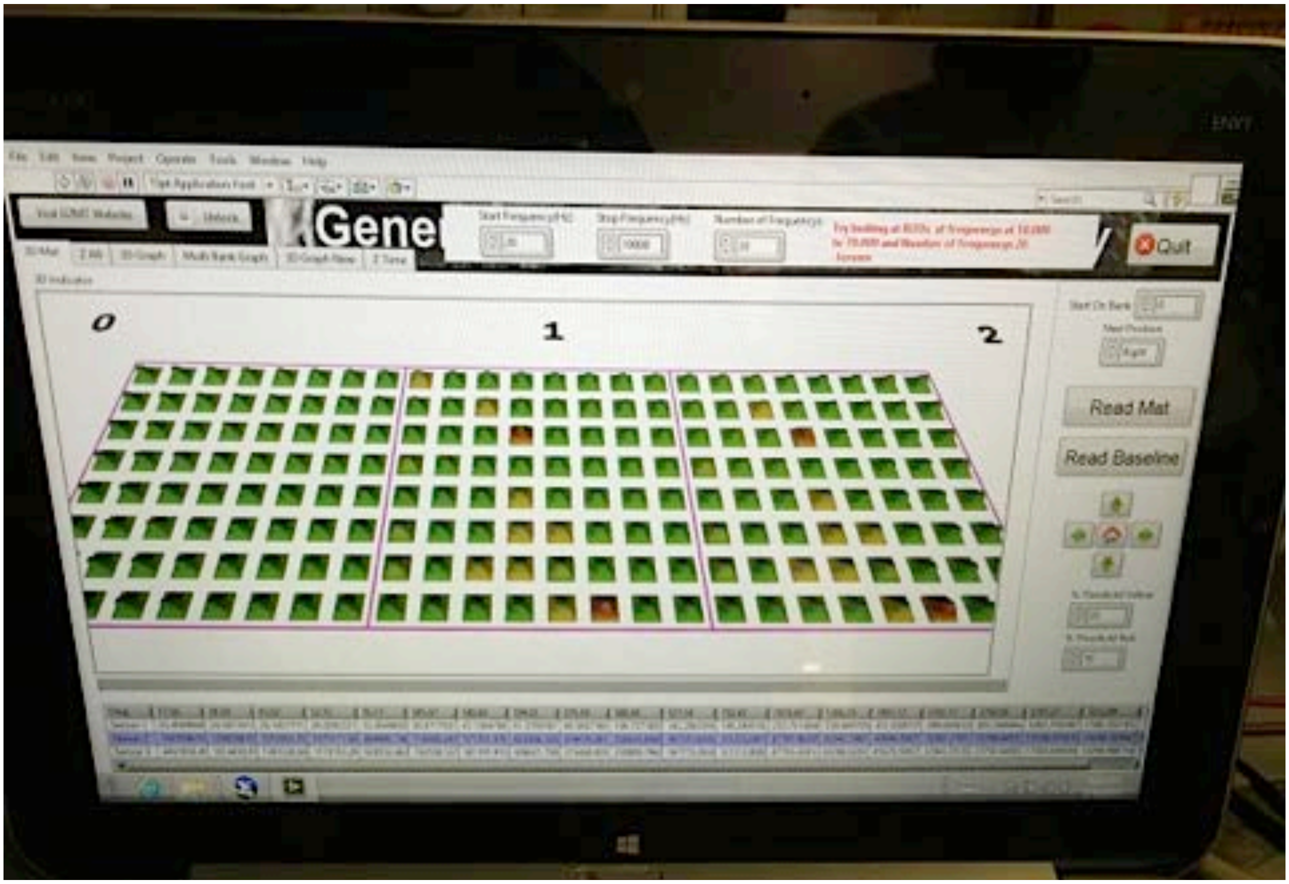


***Figure 16:  Photograph of the G2MT eStress*™ *computer program for the floppy mat system showing the data retrieved when the sensor is moved across a pipeline.  Locations 0, 1, and 2 show the three different locations where the 64 sensor set was moved around on the same pipe.***

## 6.  INDUSTRY INTEREST AND DESIRE FOR RESIDUAL STRESS SENSOR

The pipeline industry as well as many other industries have shown interest and support in the ***eStress***™ system.  Various companies have opened their doors allowing G2MT to have access to pipelines and other components during service and after damage and failures have occurred.  Our aging infrastructure has the pipeline and chemical plant owners highly concerned about the integrity of all of their steel components.  The timing for the ***eStress***™ system is perfect because it has become clear that our current integrity and risk models are insufficient and need modifications because the predicted burst pressure values for pipelines, for example, are much higher than the actual burst pressures in many circumstances.  Calculating a burst pressure of 80 ksi when realistically the burst pressure is 65 ksi can result in catastrophic failures.

Because of the success coming with the ***eStress***™ system, industry has requested G2MT to make other sensors.  Time constraints limit our ability to make every sensor that is theoretically possible, so we have focused on developing sensors that an entire industry can use.  G2MT has been funded by Shell Global Solutions to develop hydride sensors for titanium heat exchanger tubes.  The entire chemical processing and refining industry has used titanium for heat exchanger tubes for decades.  The titanium tubing has always been and is still very susceptible to cracking by the formation of brittle hydrides in the titanium.  G2MT's hydride sensors will quantify the hydride concentrations in the titanium to determine the remaining life of the tube and/or recommend replacement timing.

## 7. EXPECTED/DESIRED OUTCOMES

G2MT plans to lease and license the ***eStress***™ system to the NDE service industry. The leasing and/or licensing agreement include repair and replacement of any damaged or malfunctioning component. G2MT will market the ***eStress***™ system as a NDE tool that can be used to assess the remaining integrity of any pipeline exhibiting weldment and damage including mechanical damage and corrosion damage.

G2MT will also come out with the ***eStress***™ gauges to measure residual stress in materials while experiencing strain. The ***eStress***™ gauges are an improvement over traditional strain gauges that measure plastic strain, however, because the ***eStress***™ system measures the changes in elastic and plastic stress compared to strain gauges that can only measure plastic strain. Prototypes of the ***eStress***™ gauges are shown in Figure 17. The gauges are magnetic so they will stick to the magnetic specimens. For non-magnetic specimens, G2MT simply uses a different coil arrangement. The ***eStress***™ gauges will be the future for stress/strain measurements during mechanical testing or even on high stress components to monitor their lifespan.

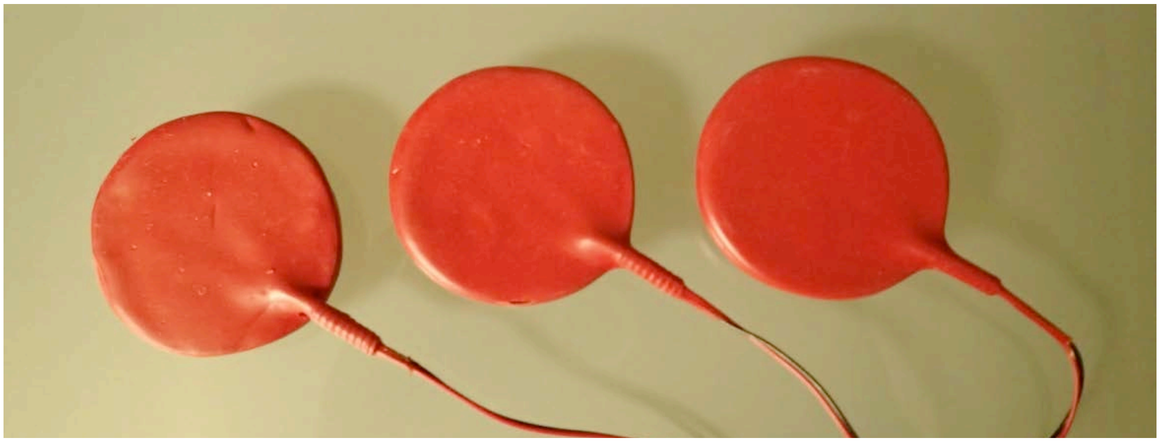

***Figure 17: Photograph of the new eStress™ gauge system. The future replacement of strain gauges.***

## 8. ACKNOWLEDGMENTS

The authors would like to acknowledge and thank multiple researchers and companies for their help and support in G2MT completing this DOT SBIR program.

- James Merritt at DOT-PHMSA for his continued support of the ***eStress***™ system and guidance leading to the commercialization of the ***eStress***™ system.
- David McColskey at the National Institute of Standards and Technology for his continued guidance on mechanical testing.
- All of the employees at Houston Metal Cutting for helping to collect, cut, store, and deliver thousands of pounds of linepipe.

## 9. REFERENCES

Alexander, C.R., Kiefner, J.F., and Fowler, J.R., “Repair of dents combined with gouges considering cyclic pressure loading”, 8th Annual International Energy Week Conference and Exhibition, Houston, Texas, January (1997).

Alexander, C.R., and Kiefner, J.F., “Effects of smooth and rock dents on liquid petroleum pipelines”, Phases 1 and 2, API Publication 1156, May (1997) and October (1999) respectively.

Alexander, C. and Kulkarni,S., “Evaluating the Effects of Wrinkle Bends on Pipeline Integrity”, Proc. Of IPC 2008, 7th Intl. Pipeline Conf., Calgary, Alberta, Canada, (2008)

American Society of Metals Handbook, Metallography, Structures, and Phase Diagrams, 8th Ed., Vol. 8, Metals Park, Ohio, (1973), pg. 261.

Baker, Michael J. Inc., “Dent Study”, TTO Number 10, Integrity Management Program, DTRS56-02-D-70036, (2004).

Baker, Michael J. Inc., “Pipe Wrinkle Study”, TTO Number 10, Integrity Management Program, DTRS56-02-D-70036, (2004).

Bray, D.E. and Stanley, R.K., *Non-Destructive Evaluation: A Tool in Design, Manufacturing, and Service,* CRC Press, Inc., Boca Raton (1997), pp 241-373.

Corbett, R.A. and Saldanha, B.J.: Metals Handbook, 9th ed., Vol.13, Corrosion, ASM International, Metals Park, OH, (1988), pp. 239-41.

Eiber, R.J., and Leis, B.N., “Line pipe resistance to outside force”, Paper 14, EPRG/PRC 10th Biennial Joint Technical Meeting on Line Pipe Research, Cambridge, April 18-21 (1995).

Fowler, J.R., Alexander, C.R., Kovach, P.J., and Connelly, L.M., “Cyclic pressure fatigue life of pipelines with plain dents, dents with gouges, and dents with welds”, Prepared by Stress Engineering Services for the Offshore and Onshore Applications Supervisory Committee of the Pipeline Research Committee, PR-201-9324, June (1994).

Hopkins, P, “The significance of mechanical damage in gas transmission pipelines”, Paper 25, EPRG/PRC 8th Biennial Joint Technical Meeting on Line Pipe Research, Paris, May 14-17, (1991).

Hopkins, P., Jones, D.G., and Clyne, A.J., “Significance of dents and defects in transmission pipelines”, Proc. Int. Conf. on Pipework Engineering and Operations, London, February 21-22, (1989).

Jackson, J.E., Mishra, B., Olson, D.L., Lasseigne, A.N., and Siewert, T.A., “The Future of Microstructural Characterization: An Electronic Metallography Laboratory”, in *34th Annual Review of Progress in Quantitative Nondestructive Evaluation*, July 23-27, 2007.

Jackson, J.E., Mishra, B., and Olson, D.L., “The Future of Microstructural Characterization: An Electronic Metallography Laboratory”, in CP975, Review of Quantitative Nondestructive Evolution, Vol. 27, pp. 1085-1092, American Institute of Physics, ed. D.O. Thompson and D. E. Chimenti, (2008a).

Jackson, J.E., Roubidoux, J.A., Mishra, B., Olson, D.L., and Lasseigne, A.N., “Assessment of Magnetocorrosion by Magnetic and Impedance Measurements”, Review of Quantitative Non-Destructive Evaluation (2008b), Chicago, Illinois, APS.

Jones, R.H., Stress corrosion cracking, ASM International, Materials Park, OH (1992).

Kumar, A.M., Hirth, J.P., Hoagland, R., and Feng, X., *J. of Testing and Evaluation*, Vol. 22, No. 4 (1994), pp. 327-334.

Lasseigne, A.N., Olson, D.L., and Boellinghaus, T., “Development of a Non-Destructive Tool for Assessment of Residual Stress in Welds”, Proc. of ASNT Fall Conf. 2004, pp. 141-143, Las Vegas, NV, USA, 15-19, November (2004), ASNT, Columbus, OH, (2004).

Lasseigne, A.N., Anton, J, Jackson, J.E., Olson, D.L., and Mishra, B., “Development of Electromagnetic Techniques for Hydrogen Content Assessment in Coated Linepipe”, Rev. of QNDE 2006, pp. 1159-116, American Institute of Physics, Melville, N. Y. (2007a).

Lasseigne, A.N., Mishra, B., and Olson, D.L., “Characterization of Hydrogen Storage Capabilities in Advanced Battery Materials”, Materials and Manufacturing Processes, 22, pp, 433-439, (2007b).

Lasseigne, A.N., Anton, J.M., Siewert, T.A., Olson, D.L., Mishra, B., and Jackson, J.E., “Advanced Nondestructive Measurement Schemes to Actively Monitor Hydrogen Content in Steel Pipeline”, in CP975, Review of Quantitative Nondestructive Evolution, Vol. 27, American Institute of Physics, eds. D.O. Thompson and D. E. Chimenti, (2008c) pp. 1117-1124.

Lasseigne, A.N., Koenig, K., McColskey, J.D., Siewert, T.A., Olson, D.L. Jackson, J.E., and Mishra, B., “Advanced Non-Destructive Hydrogen Content Sensors”, ACerS, Proceedings of Materials Innovations in an Emerging Hydrogen Economy, Cocoa Beach, FL (2008a).

Lasseigne, A.N., McColskey, J.D., Koenig, K., Jackson, J.E., Olson, D.L., and Mishra, B., “Advanced Non-Contact Diffusible Hydrogen Sensors for Steel Weldments” ASM Trends in Welding Research, Pine Mountain, Georgia (2008b).

Lasseigne, A.N., Koenig, K., McColskey, J.D., Jackson, J.E., Olson, D.L., Mishra, B., and Siewert, T.A., "Non-Destructive Determination of the Diffusion Coefficient of Hydrogen", 2008 International Hydrogen Conference: Effects of Hydrogen on Materials, Jackson Hole, Wyoming, (2009).

Lasseigne, A.N., and Olson, D.L., “Development of Nondestructive Techniques for Characterization of Residual Stresses in Advanced Materials”, *Materials Evaluation*, October, (2008), pp 1077-1083.

Maxey, W.A., 1986, “Outside force defect behaviour”, NG-18 Report 162, AGA Catalog no. L51518.

Mishra, B., Jackson, J.E., Lasseigne, A.N., and Olson, D.L., “Generation II Materials Science to Achieve New Methods to Design, Process and Inspect Welds and Joints Necessary for Full Utilization of Advanced Materials”, Proceedings of ICMT 2008 Conference, pp. 1-10, Chennai, India, February (2008).

Olson, D.L., Lasseigne, A.N., Jackson, J.E., Mishra, B., Koenig, T.A., and Madeni, J.C., “Weld Assessment by Thermoelectric Power Measurements”, for Proceedings of the International Conference of Welding and Joining of Materials 2007, Cusco, Perú 16 – 18 April 2007.

Olson, D.L., Jackson, J.E., Mishra, B., Kaufman, M.J., Siewert, T.A., Lasseigne, A.N., Pinkas, M., and Landau, A., “Generation II Materials Science for Welds and Advanced Materials”, ASM Pine Mountain, Trends in Welding Research, Pine Mountain, Georgia (2008b).

Olson, D.L., Kaydanov, V.I., Landau, A., Pinkas, M., and Lasseigne, A.N., “Application of Interdisciplinary Fundamentals to Achieve New Insight into Materials Properties, Stability and Integrity”, in CP975, Review of Quantitative Nondestructive Evolution, Vol. 27, pp. 3-22, American Institute of Physics, ed. D.O. Thompson and D. E. Chimenti, (2008a),

Rosenfeld, M.J., “Investigations of dent rerounding behaviour”, Proc. Int. Pipeline Conference, 1, pp. 299-307, Calgary, Canada, (1998).

## APPENDIX A: *eStress*™ SYSTEM USER MANUAL

**G2MT, LLC**

***eStress***™ **USER MANUAL**

### Notices

The information contained in this document is subject to change without notice.



### Manual Printing History

September 2014 First Edition – Version 1

### Safety Summary

The following general safety precautions must be observed during all phases of operation of the components of the ***eStress***™ System. Failure to comply with these precautions or with specific WARNINGS elsewhere in this manual may impair the protection provided by the equipment. Such noncompliance would also violate safety standards of design, manufacture, and intended use of the equipment. G2MT, LLC assumes no liability for the customer's failure to comply with these precautions.

- Ground the System Components. When any of the instruments, including the computer, are operated under AC power ensure that they are grounded with the supplied 3-pole power cable grounding prong.
- DO NOT operate in an explosive environment. Do not operate the instruments in the presence of inflammable gases or fumes. Operation of any electrical instrument in such an environment clearly constitutes a safety hazard.
- DO NOT Service or Adjust the Instruments. Operators must not remove instrument covers. Component replacement and internal adjustments MUST be made by qualified G2MT maintenance personnel ONLY.
- People with pacemakers should consult their physician(s) before use. Electromagnetic fields in close proximity to heart pacemaker could cause pacemaker interference or pacemaker failure.
- Dangerous Procedure Warning. Warnings in this manual, such as the example below, precede potentially dangerous procedures. Instructions contained in the warnings must be followed.

**WARNING** – Dangerous voltage levels, capable of causing harm, are present in this instrument. Use caution when handling.

### Warranty

This G2MT system and its components are warranted against defects in material and workmanship for a period corresponding to the individual warranty period of its component products. Instruments are warranted for a period of one year. During the warranty period, G2MT will, at its option, either repair or replace products that prove to be defective.

For warranty service or repair, the products in question must be returned to a service facility designated by G2MT. The Buyer shall prepay shipping charges to G2MT, and G2MT shall pay shipping charges to return the product to the Buyer. However, the Buyer shall pay all shipping charges, duties, and taxes for products returned to G2MT from another country.

G2MT warrants that its software and firmware designated by G2MT for use with an instrument will execute its programming instructions when properly installed on that instrument. G2MT does not warrant that the operation of the instrument, or software, or firmware, will be uninterrupted or error free.

**Limitation of Warranty**

The foregoing warranty shall not apply to defects resulting from improper or inadequate maintenance by the Buyer, Buyer-supplied software or interfacing, unauthorized modification or misuse, operation outside the environmental specifications for the product, or improper site preparation or maintenance.

Important – No other warranty is expressed or implied. G2MT specifically disclaims the implied warranties of merchantability and fitness for a particular purpose.

**Contents**



**Unpacking and Preparation**

After you receive the ***eStress***™ System, carry out checks during unpacking according to the following procedure:

- Check that the packing box used to package the system is not damaged.
- Referring to Table 1, check that all packaged items supplied are present.
- Check the packaged items supplied with the system for any damage or defects.

**Table A.1: Items Supplied as part of the *eStress*™ System**

| PRODUCT NAME | PART NUMBER | QTY |
|---|---|---|
| ***eStress***™ Data Acquisition Console | C-1-64-DAQ | 1 |
| HP Beats Audio Envy PC | HP Envy | 1 |
| USB Cable | USB A-B | 1 |

| | | |
|---|---|---|
| ***eStress***™ Sensor Mat | SM-64-220 | 1 |
| Mat Extension Cable – 6 ft | C-6-25 | 4 |
| DC Power Adapter – 15VDC | PA-DC15 | 1 |

Prepare system for use according to the following procedure:

- Open ***eStress***™ Data Acquisition Console's Case.
- Connect USB cable between ***eStress***™ Data Acquisition Console and HP Beats Audio Envy PC.
- Connect DC Power Supply – 15VDC to the ***eStress***™ Data Acquisition Console.
    - Allow a minimum of three hours for the batteries to take on charge if planning on using the system under battery power.
- Connect the Sensor Mat to the ***eStress***™ Data Acquisition Console with the Mat Extension Cable.
- Turn on the computer and run the ***eStress***™ program called eStress.exe by double clicking on its icon.

**Environmental Requirements**

Set up the ***eStress***™ System where the following environmental requirements are satisfied:

Ensure that the Operating Environment meets the following requirements

| | |
|---|---|
| Temperature | 0 °C to 55 °C |
| Temperature Range at Calibration | 23 °C ± 5 °C |
| Humidity | 15% to 85% at temperatures <40 °C |
| Altitude | 0 to 2,000 m (0 to 6,561 ft) |
| Vibration | Max. 0.5 G, 5 Hz to 500 Hz |

The environmental requirements listed above are NOT for the specifications and measurement accuracy of the ***eStress***™ System, but for its operating environment.

**Overview**

## Product Introduction

The ***eStress***™ System is a special-purpose through-thickness residual stress meter for use primarily in operating steel pipeline. It can be used as part of a preventive maintenance schedule, as a quality control tool, as an integrity assessment tool, or for laboratory use. The measurements are performed on the exterior of the steel pipeline.  Special pipeline coatings do not have to be removed for proper residual stress measurements.

The ***eStress***™ System directly measures the residual stress at the steel lattice level by measuring changes in the localized energy beneath the sensor probes. The changes in localized energy are calibrated to well-known standards, so that the change in localized energy can be correlated to a quantified residual stress in the axial, radial, and hoop directions.

The ***eStress***™ System is composed of an array of sensors, a data acquisition console, and a laptop computer that runs the software required to generate, read, and record signals. It can be run battery-powered or with a DC power supply.

## System Details

The ***eStress***™ System configuration is shown in Figure 1 below.

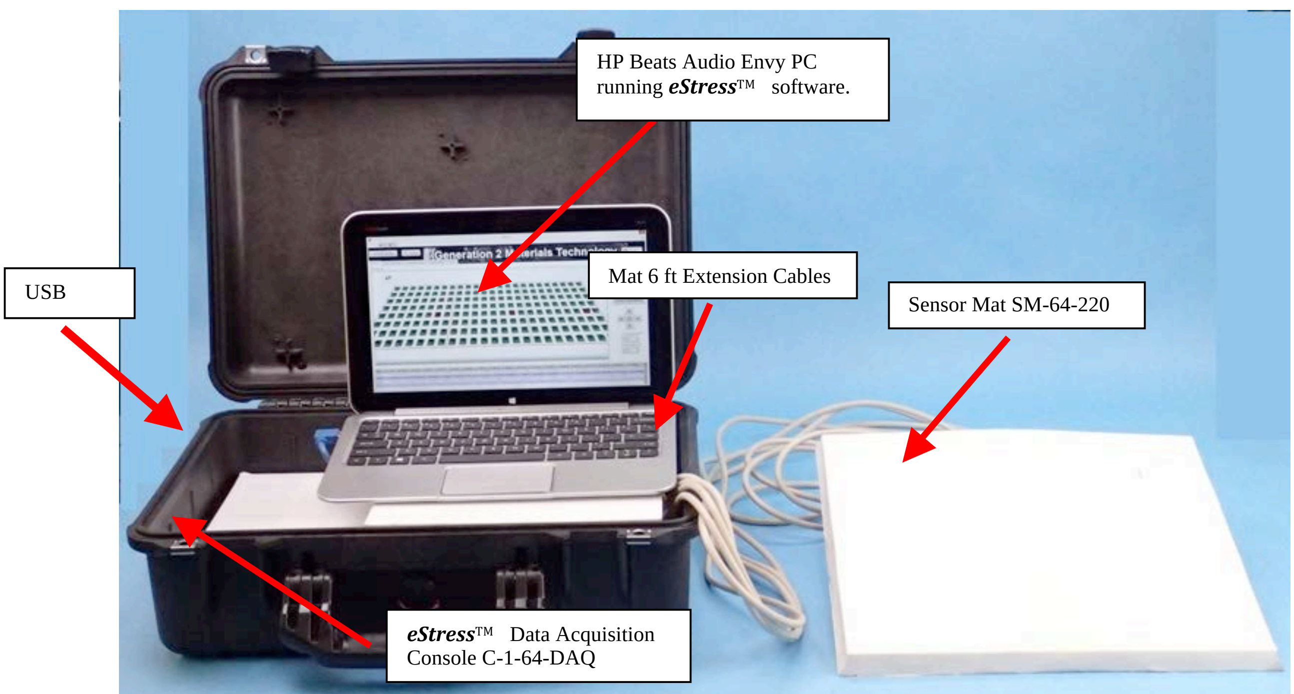


***Figure A.1: The eStress™ System***

The ***eStress***™ System can be supplied with custom Sensor Mats containing between 1 and 64 sensors according to the application. If more sensors are required the console can be customized to accommodate the requirements.

## Operation

Follow the steps described below to operate the system:

- Connect the system components (USB cable between console and computer, and Mat Cables between Mat and Console) together.
- Switch the power switch to ON (switch is located internally on the right side of the Console; not shown in Figure 1).
- Turn PC ON
- Double click on the ***eStress***™ software icon to launch the program.
- Select "Run" on the screen, either by using the mouse and clicking on the Run button or by selecting it with your finger via the touch screen.
- Position the ***eStress***™ Sensor Mat on a location of the unit under test that is known to be safe of observable defects (refer to Figure 3). **Attention:** Ensure that the Mat is flat against the surface being measured. This area will be used to determine the baseline to use for further measurements.
- Select the "Read Baseline" button shown on the screen (with the mouse or with your finger on the screen). Refer to Figure 2 below for location.
- Wait for the Progress Bar to grow from left to right to the end of the chart, this bar indicates the data collection process status.
- Position the ***eStress***™ Sensor Mat on the location of the unit under test that is deemed suspect. **Attention:** Ensure that the Mat is flat against the surface being measured.
- Select the "Read Mat" button shown on the screen (with the mouse or with your finger on the screen). Refer to Figure 2 below for location.
- Wait for the Progress Bar to show that the data has been collected.
- If it is desired to measure another area that is deemed suspect select the "Next Position" drop-down menu button; through this you identify the place where you will place the Mat so it is properly displayed in the graph. See Figure 2 for location.
- Position the ***eStress***™ Sensor Mat on the location of the unit under test that is deemed suspect. **Attention:** Ensure that the Mat is flat against the surface being measured.
- Select the "Read Mat" button on the screen.
- Once that data has been collected, and the graph has displayed the second location that was measured, you can use the "Next Position Viewer" buttons to center the graph on the area you would like to observe. To return to the first measurement taken select the "Home" button (at the center of the arrows).
- Repeat the process for as many locations as you would like to measure.
- The graph will show a visual representation of what the sensors are measuring; if the sensor location is green it indicates that there is no noticeable difference between the area that was selected as the Baseline and the area being measured. Yellow and Red will indicate progressively increasing differences in that area as compared to the Baseline, therefore they can be treated as suspect areas.

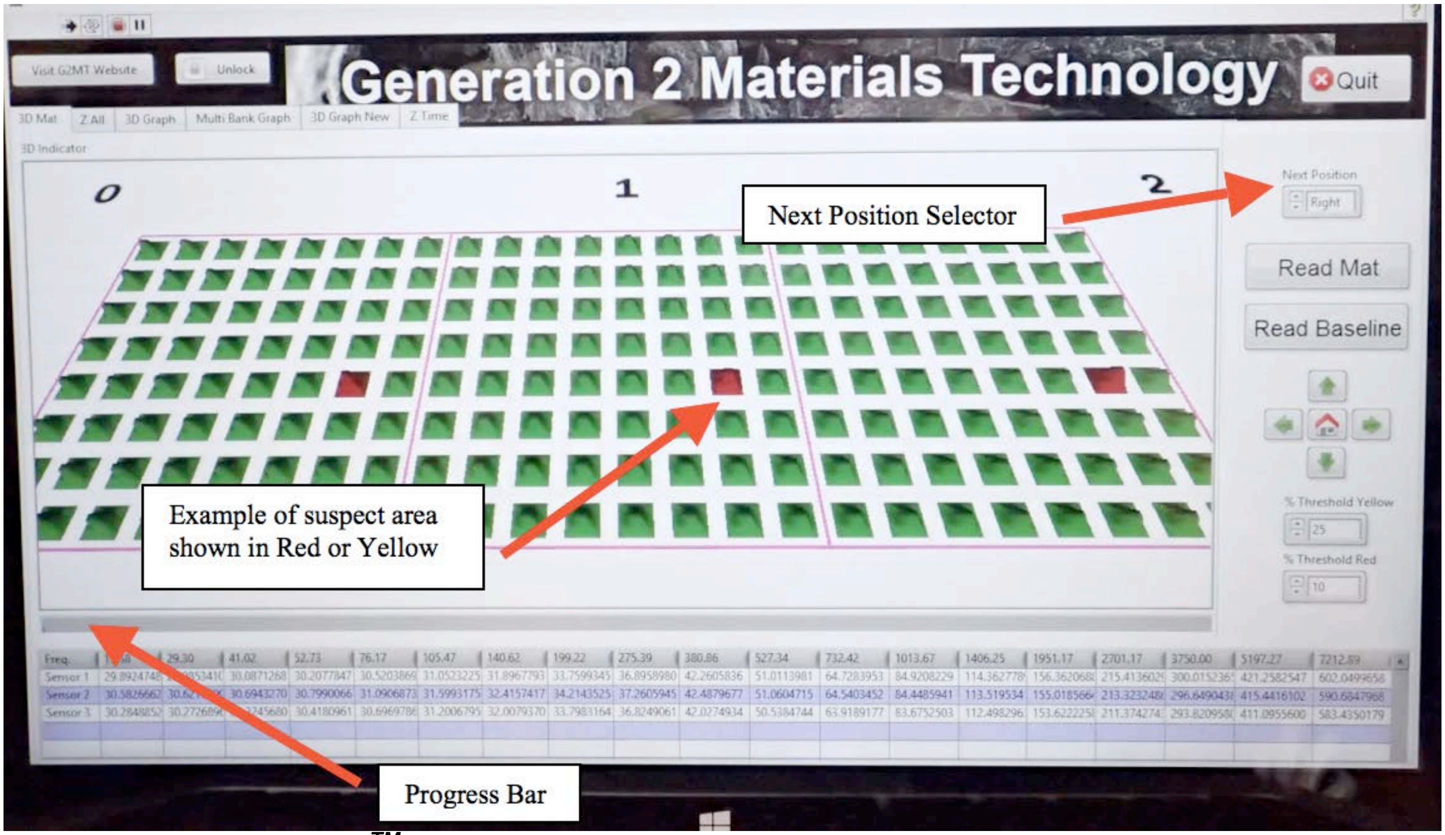

***Figure A.2: The eStress™ main software screen.***

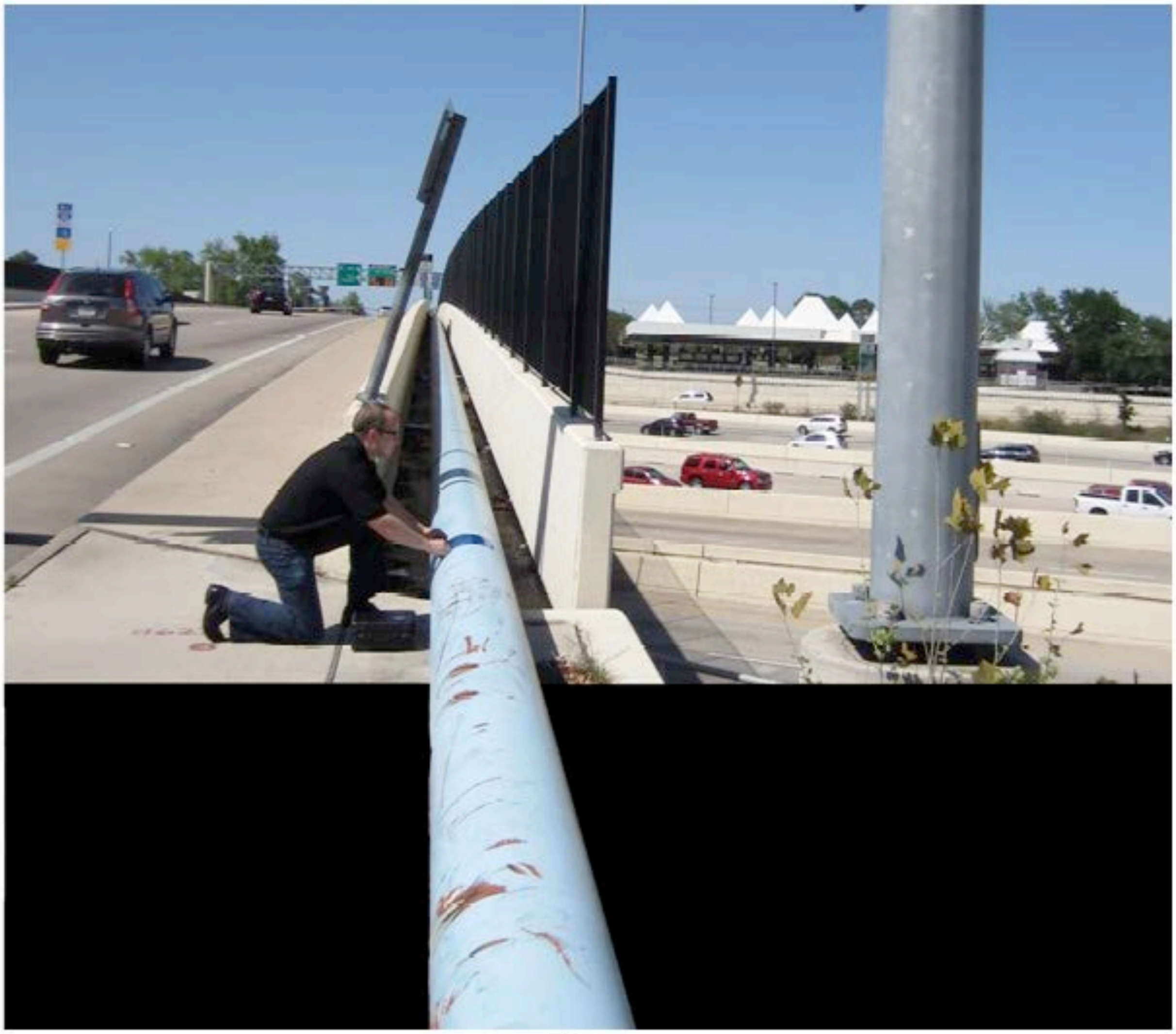

***Figure A.3: Application of the eStress$^{TM}$ System.***

**Data Management**

Please call G2MT Customer Service department for help with the interpretation and management of data generated during operation of the ***eStress***$^{TM}$ System.

G2MT, LLC reserved the right to interpret the data as a service offered to the customer.

**Troubleshooting**

In the event of a malfunction of the system or any of its components **DO NOT** attempt to address the problem alone; please call G2MT Customer Service for instructions and troubleshoot support. This will help us ensure any questions related to functionality and warranty are properly addressed.