Intellectual Merits

This Small Business Innovation Research (SBIR) Phase I project will demonstrate extensometer and associated calibrator designs that exhibit an order-of-magnitude improvement in resolution and stability. Evolving aerospace and automotive structural materials require these instruments. For example, intermetallics can increase service temperatures and efficiency while reducing weight. Existing extensometer performance is insufficient to study these materials due to small strains of interest.

Existing technologies will be combined in a novel way to meet project goals, eliminating the risk associated with developing completely new technologies. Specific technologies and design concepts are detailed in the Project Description due to their proprietary nature.

The proposed technical tasks are as follows: 1) complete preliminary designs, 2) acquire and integrate core extensometer components, 3) acquire and integrate core calibrator components, 4) evaluate prototype performance, and 5) identify needed enhancements. Performance targets are the following: extensometer: 10 nm resolution, 50 nm drift, and calibrator: 5 nm resolution, 25 nm drift.

The SBIR team has extensive experience with instruments of these types. Previous experience includes design and development of precision medical devices, extensometers, calibration equipment, test automation software, electronics, and optics systems. Both of the principal investigators are senior researchers with a minimum of twenty years of relevant experience each.

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Broader Impact

The program results will be fundamental enabling instruments. Researchers will use these instruments to improve a wide range of products through better understanding existing material performance and development of improved materials. New material applications and behavior concepts will come to light as these instruments are used to study the details of specific types of material behavior. These benefits will affect the transportation, aerospace, power generation, and construction industries.

In marketing terms, the instruments resulting from this program will be similar to units already available from various vendors. Using current design concepts, the cost of these enhanced instruments will be the same as, or less than, the best current instruments. Alternate means to meet the program objectives have been discussed at length. Neither the SBIR team nor the major commercial vendors were able to identify a viable and cost-effective alternative.

Brystin Research and Development has previous SBIR successes, including commercialization of SBIR project technologies. The SBIR team has close partnerships with major instrument vendors to facilitate eventual technology commercialization. These relationships include industry financial support for commercialization of previous SBIR results. These relationships provide excellent opportunities for industry contributions to the commercialization of the program results.

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Key Words

Extensometer, calibrator, displacement, resolution, stability, material, material testing, material characterization, optics, laser, interferometer, magnetostriction, LVDT, CTE, drift, instruments, elevated temperature, automotive, aerospace, power generation

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Topic Name and Subtopic

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PROJECT DESCRIPTION

Part 1: Identification and Significance of the Innovation

Brystin Research and Development proposes to develop two new, related instruments. The first instrument will be a new extensometer for material characterization with a resolution approximately an order-of-magnitude better than the best extensometers currently available. The extensometer will be designed for use at temperatures from -200ºC to approximately 1000ºC. The second instrument will be a calibrator capable of calibrating the new extensometer. The calibrator will be more than an order of magnitude more precise and repeatable than the best calibrator currently available for field use. Together, these two instruments will significantly enhance the ability of a researcher to study the details of material behavior in the small-strain regime. In addition, researchers studying long-term changes in materials will benefit greatly from the significantly enhanced stability of the new extensometer.

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Part 2: Phase I Technical Objectives

The overall objective of the project is to provide researchers, quality control engineers and technicians, and others with a substantial improvement in their ability to measure displacements and strains in both benign and severe thermal environments. Recent advances in material development have resulted in ceramics and intermetallics with higher temperature capability and/or lower density than traditional metals or superalloys. These materials typically exhibit behavior of interest at much lower strains than conventional metals. Thus, there is a pressing need for improvement in displacement measurement technology (extensometry) to keep pace. No commercial vendor has been successful in developing a new technology, or in combining existing technologies, to meet this demand for an improved extensometer.

Brystin has evolved a concept for combining existing technologies in a novel way to meet the need for a significantly better extensometer and associated calibrator. The following technical objectives must be met to demonstrate this innovative technology combination:

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1. Evaluate the preliminary extensometer and calibrator design concepts.
2. Acquire and integrate core extensometer components with additional existing laboratory apparatus at Brystin.
3. Acquire and integrate core calibrator components with additional existing laboratory apparatus at Brystin.
4. Evaluate the prototype extensometer and calibrator performance.
5. Identify changes/enhancements required to meet the performance targets.

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Performance targets for the extensometer are 10 nm resolution with 50 nm maximum drift; performance targets for the calibrator are 5 nm resolution with 25 nm maximum drift. These targets were chosen to meet the needs of researchers, at universities and national laboratories, who have expressed interest in an improved extensometer.

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Another key issue for widespread acceptance of the new instruments is that costs be kept to a reasonable level. Preliminary designs rely on commercial off-the-shelf components for most of their functionality. This allows Brystin to keep the cost of the new instruments at, or below, the cost of the best currently available instruments.

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Part 3: Phase I Research Plan

BACKGROUND

New materials, and better understanding of existing materials, have been two cornerstones of advancing technology from the industrial revolution through the information age. It is already clear that this key role for material development will continue into the foreseeable future. One of the most important drivers of this trend is the availability of measurement systems capable of collecting data about the more sophisticated aspects of how materials perform.

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One of the most widely used instruments in material characterization is the extensometer — a device that measures the small displacements that occur when materials are subjected to mechanical loads, temperature changes, and other service conditions. Although a number of non-contacting extensometer types are available, the mainstay of displacement and strain measurement in material characterization tests is the contact extensometer as shown in Figure 1. These extensometers typically consist of

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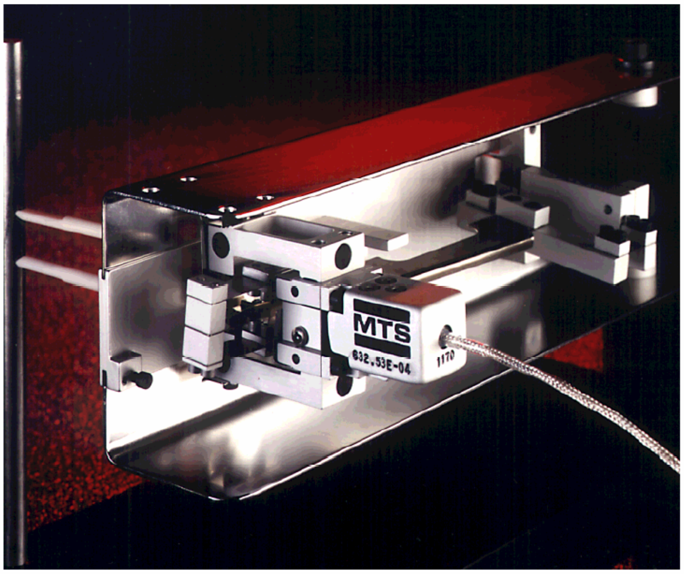

Figure 1. Typical Commercial Elevated Temperature Extensometer.

a main body containing the actual sensor and two extension rods that make contact with the material being studied. The extension rods transmit the displacement on the material surface to the sensor in the extensometer main body. In elevated temperature testing, the extension rods may also serve to keep the sensing system out of the elevated temperature area. In the example shown in Figure 1, a metal heat shield is in place between the extensometer main body and the material being tested.

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In addition to the extensometer itself, a calibration device is needed that can enforce known, precise displacements on the ends of the extension rods while the voltage output of the extensometer sensor is monitored. The calibration procedure allows conversion of voltage measurements from the extensometer to the actual displacements on the material surface. The calibrator is a reference device for the extensometer and thus, should be more accurate and have better resolution than the

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extensometer. In this sense, the calibrator is the more difficult instrument to design and build.

Despite the current availability of commercial extensometers and calibrators, a need still exists for better instruments. As previously stated, new materials and a better understanding of existing materials will continually fill this need. Various laboratories and industries are now working with materials that exhibit behaviors of interest at very small displacement levels. While existing extensometers have worked well up to this point, researchers are finding that these instruments simply do not have the required resolution and stability to study the current generation of intermetallics and ceramics. The situation will continue to grow in urgency as the next wave of new materials enters the scene. This, then, is the motivation for the proposed SBIR Phase I project.

PROPOSED CONCEPT

The proposed concept consists of two major, but complementary instruments: the extensometer and the calibrator. The extensometer is the instrument used by researchers and scientists to study various material behaviors. It is attached to the material specimen or component to be studied and converts the extremely small displacements on the surface into measurable electrical signals. It is necessary to know the relationship between the surface displacement and the output voltage. The calibrator is used to determine this relationship. The extensometer is attached to the calibrator in much the same way it is attached to a specimen or component. The calibrator is capable of moving the two contact points of the extensometer in an extremely precise and known fashion, so that the calibrator movement may be combined with the associated extensometer voltage output to produce the required relationship. In a typical setting, the calibrator is used to periodically verify the output of the extensometer.

The major challenges to developing a substantially improved extensometer are threefold. First, the mechanical design and sensing system must be capable of resolving the expected displacements. A calculation for a typical low-strain material shows the following:

Full scale material strain:	0.001 mm/mm = 0.1% = 1000 μstrain
Desired extensometer gage length:	5 mm
Full scale material displacement:	0.001 mm/mm * 5 mm = 0.005 mm = 5 μ m
Desired resolution:	0.1% full scale = 0.001 * 5 μ m = **5 nm**

Second, the extensometer must be stable under the expected operating conditions. The fundamental sensing system must be inherently insensitive to temperature changes, humidity changes, electronic noise, and other environmental factors common in a typical measurement setting. Finally, the extensometer physical design, mass, and mounting method must all be compatible with small strain measurement on typical specimens and components in the expected measurement setting.

Given the extensometer performance requirements, we must have a calibrator capable of verifying that the extensometer is performing properly. The calibrator design faces the same three major requirements as the extensometer. Thus, the proposed extensometer and calibrator must both meet the following criteria:

1. Measurement resolution
2. Measurement stability
3. Suitability to a typical measurement environment

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EXTENSOMETER CONCEPT

The SBIR team has studied the use of extensometers in typical measurement situations and determined that the physical layout of existing extensometers is quite good with respect to ergonomics and testing requirements. Thus, to eliminate the risk associated with a new physical layout, the team will maintain the general physical design of existing extensometers in the new instrument. The extensometer will address the criteria above by combining three distinct technologies and design concepts within the traditional extensometer physical layout.

Monolithic Extensometer Body

The extensometer body must be capable of moving in one degree-of-freedom only. It must also exhibit the smallest possible deviation from linearity in that degree of freedom, and the smallest possible hysteresis. Experience has shown that any type of mechanical joint, no matter how tightly coupled, is far inferior to a solid-state coupling with respect to linearity of motion and hysteresis. Thus, the extensometer body will be constructed as a single, monolithic component. This introduces the issue of allowing motion in only one degree of freedom while using a monolithic component. The design addresses this problem with an integral flexure with dimensions that make it extremely rigid in all degrees of freedom except the desired one. Figure 2 illustrates the design concept. Note that the flexure is thin enough to allow rotation about the Y-axis without damage to the flexure material. At the same time, the short Z dimension and long Y dimension of the flexure restrict the other relative rotations and displacements of the upper and lower extensometer body.

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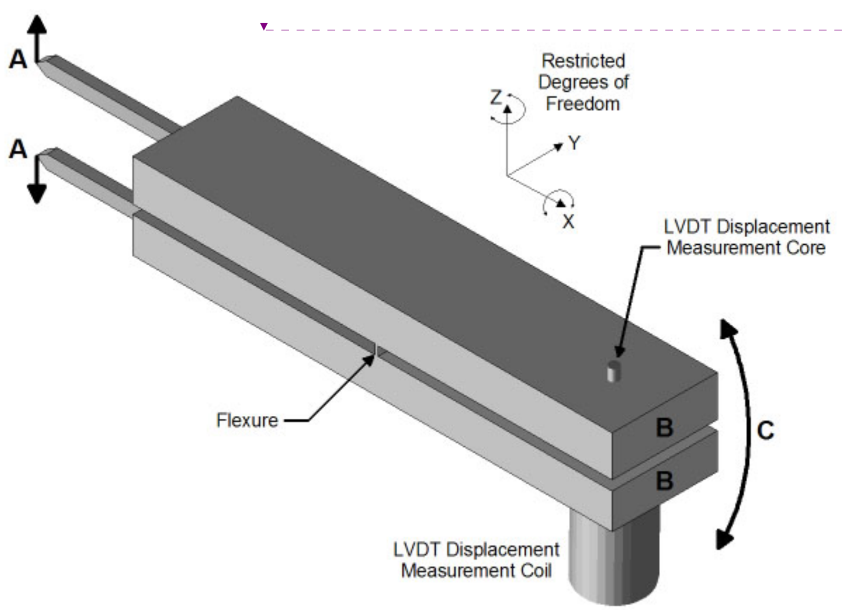

Figure 2. Extensometer Design Concept.

The exact flexure dimensions will be determined during the Phase I effort, but preliminary experiments have demonstrated the ability to construct this type of device. Furthermore, these tests have shown that the flexure can meet the deflection requirements without permanent damage, even after millions of flexing cycles.

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Linear Variable Displacement Transformer (LVDT) Displacement Sensor

Almost all existing extensometers use strain gages as the active sensing elements. This type of extensometer has demonstrated significant sensitivity to ambient humidity changes due to the nature of the strain gage sensing elements. The proposed extensometer design uses an LVDT sensor that does not exhibit this sensitivity. The LVDT coil is hermetically sealed and preliminary experiments show it to be very insensitive to ambient humidity and temperature changes during measurements. In addition, recent development of miniature LVDT coils and cores has reduced the mass of these devices to about 5g. This low mass is easily incorporated as an extensometer active sensing element. Finally, new electronic signal conditioning and improved construction methods provide the required sensitivity in the miniaturized LVDT. Careful choice of electronics settings and the LVDT coil and core can produce sensors capable of resolving displacements of 1 nm. Combining this sensitivity with the physical design of the extensometer body, the extension rod design, and the position of the flexure, it is possible to produce an instrument with resolution smaller than the target of 5 nm. Figure 2 illustrates the position of the LVDT sensing coil on the extensometer. The LVDT coil travels with the lower extensometer body arm and the core travels with the opposite (upper) extensometer body arm.

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Zero Coefficient of Thermal Expansion (CTE) Extensometer Body Material

A principal cause of instability in mechanical measurement devices is the change in dimension of parts with temperature. Typical materials used in extensometers, such as aluminum and steel, exhibit CTE values between 10x10^{-6}/ºC and 25x10^{-6}/ºC. The proposed extensometer will be made from a Nickel-Iron alloy, Invar 36, which exhibits a CTE of about 1x10^{-6}/ºC. This material reduces the inherent sensitivity of the extensometer body to ambient temperature changes by an order-of-magnitude.

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CALIBRATOR CONCEPT

The proposed next-generation extensometer is not useful unless there is a way to determine the relationship between the voltage output from the instrument and the actual displacement on the specimen or component surface. The National Institute of Standards and Technology (NIST) has primary reference standards and calibration capabilities to provide this relationship; however, sending the extensometer to NIST for calibration is time-consuming and expensive. To be truly practical, the extensometer must have a companion calibration device that has the required accuracy and stability to perform field calibrations that are traceable to NIST reference standards. Thus, the SBIR team will design and construct such a calibrator.

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As with the extensometer, the SBIR team will avoid the risk associated with developing a totally new technology. Instead, the calibrator will be developed by combining already proven technology in a new way. The calibrator will address the three criteria listed in the Proposed Concept Subsection using the following four technologies and design concepts: monolithic calibrator chassis, solid state calibrator actuator, HeNe laser interferometer monitor, and closed loop calibrator control.

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Monolithic Calibrator Chassis

The calibrator chassis must be capable of holding all the other calibrator components in fixed relative positions under typical field environmental conditions. From experience, the primary issues to be addressed are the stiffness of the chassis and its ability to avoid dimensional change due to ambient temperature changes. So long as the calibrator can be transported by a single person, weight is not a crucial factor. The

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stiffness issue can therefore be easily addressed by using thick chassis components. In addition, making the chassis from a single, monolithic piece of material eliminates any movement associated with mechanical joints. Figure 3 shows a cut-away view of the overall calibrator design concept including the monolithic chassis.

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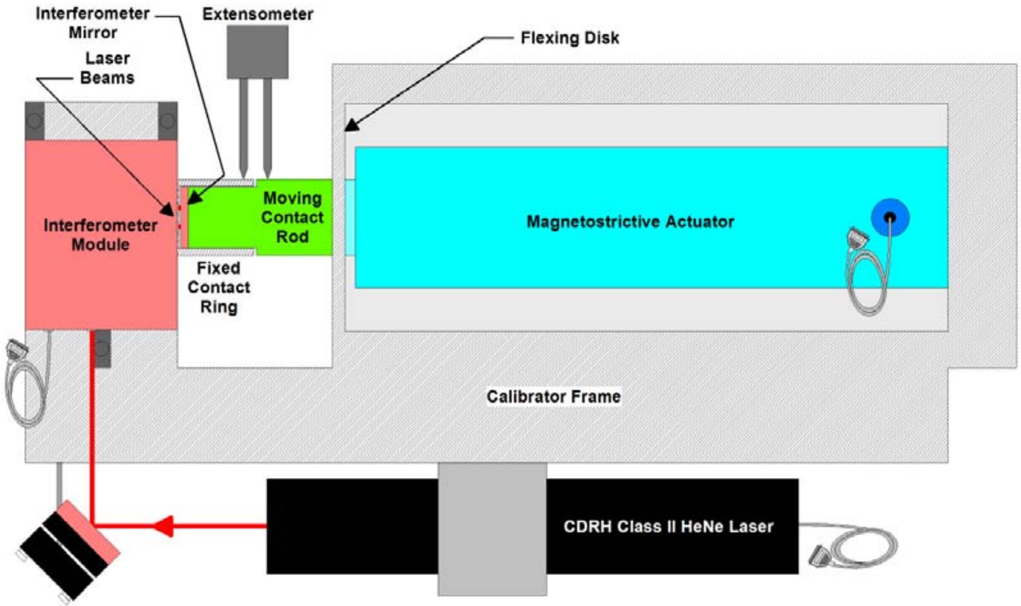

Figure 3. Cut-Away View of Calibrator Design Concept.

With respect to dimensional changes due to temperature variations, the SBIR team will construct the calibrator from the same INVAR 36 alloy as proposed for the extensometer. This reduces the changes in relative position of the critical components to a negligible level.

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Solid-State Calibrator Actuator

One of the most critical aspects of the calibrator design is ensuring that the motion of the extensometer contact components is a displacement in one dimension only. No significant rotational or transverse displacements can be allowed. The SBIR team will borrow a technology they already use successfully in the high-frequency testing field: a solid-state magnetostrictive actuator.

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The calibrator actuator will consist of a magnetostrictive actuator within a cylindrical cavity with one rigid end and one relatively flexible end. The magnetostrictive actuator is a commercial off-the-shelf unit capable of producing displacements up to approximately 0.1 mm with an associated force of approximately 2.2 kN. Since the actuators are analog devices, their displacement resolution is, in theory, infinitely small. In practice, these actuators have been used to produce displacements as small as 1 nm – well below the required displacement resolution for the calibrator.

The relatively flexible end of the actuator cavity is a disk of material left in place after machining the cavity. The disk is extremely stiff in the two lateral displacement directions as well as in the three rotation directions. The only degree of freedom in which the disk moves relatively easily is the axial flexing direction — exactly the direction

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required to produce relative axial displacements between the moving contact rod and the fixed contact ring shown in Figure 3. The disk will be made as thick as possible while still allowing the magnetostrictive actuator to produce the required motion within its rated force capacity. The exact dimensions will be determined as part of the Phase I effort.

An additional advantage of the magnetostrictive actuator is that, once the extensometer is mounted on the calibrator, the operator does not touch the calibrator until the calibration is complete. Physical operator interaction with the calibrator is a substantial source of error when dealing with displacements in the nm range.

HeNe Interferometer Displacement Monitor

Knowing the actual displacement of the extensometer contact points to the required resolution and accuracy is a second critical aspect of the calibrator design. The SBIR team will use an off-the-shelf Helium-Neon (HeNe) laser interferometer module in a dual-path configuration as shown in Figure 3. The inherent sensitivity of this system is 2 fringes per wavelength of the laser light, or 1 fringe = 316 nm. Previous experience with laser interferometers used in material characterization labs shows that it is practical to obtain sub-fringe interpolation to approximately 1/500th of a fringe. Thus, the estimated resolution of the system is 316 nm / 500 or about 0.6 nm. This is considerably less than the required resolution leaving a satisfactory safety margin for unforeseen resolution degradation as the design is tested and refined.

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Figure 3 demonstrates good interferometer practice in the design concept. Issues such as Abbé errors and short dead path length have been carefully considered and accounted for within the design.

The HeNe interferometer displacement measurement is also accepted as a standard by NIST, offering an obvious advantage; a field calibrator based on the HeNe interferometer may be used as a traceable reference without periodic NIST certification. Sending the calibrator to NIST for certification on a periodic basis is still recommended practice, but does not pose as significant an issue as certifying each extensometer in a laboratory.

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Closed-Loop Calibrator Control

Since the actuator is controlled by a drive voltage and the actual calibrator displacement is measured by an interferometer, an obvious step in improving the calibrator stability is closing the loop with a microcomputer and actively controlling the displacement. This has several advantages. First, as previously mentioned, physical operator interaction with the calibrator is a significant source of vibration and calibration error. Closing the loop obviates the need for any operator contact with the calibrator. Second, any drift in the displacement that occurs during a measurement can be corrected automatically. Thus, residual effects of thermal expansion and small instabilities in the magnetostrictive actuator can be removed and will not enter into the calibration measurements. Third, removing the operator from the loop not only makes calibration more convenient, it minimizes the chances of an error entering the procedure.

The plan to achieve each objective.
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