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DESIGN OF A HIGH PRECISION DILATOMETER USING LASER INTERFEROMETRY

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Thermophysical Properties - 5842

Abstract

This study examines the design of a high precision dilatometer which utilizes laser interferometry as the basis for the length measurement system. The dilatometer is being designed for operation from ambient to 800°C using samples which require minimal preparation. Several interferometric techniques useful to dilatometry were reviewed from the literature. As a result of this review and establishment of performance criteria, a technical design is proposed. The optical design incorporates a two-frequency He-Ne laser with arc detection in a modified Michelson interferometer. A vertical sample/furnace configuration appears to offer a number of design advantages. Operational considerations and dilatometer development costs are also presented.

I. Introduction

There is a need for high temperature dilatometric measurements with a precision greater than can be obtained by conventional push-rod dilatometers. An example of this need is the matching of thermal expansion coefficients of glass-ceramic and metal components used in sealing applications. In this report, the use of laser interferometry is examined as a technique for high precision dilatometry in both the research laboratory and in a production environment as a quality control instrument. After a survey of measurement techniques used by other investigators, a technical design is presented.

Several design options and tradeoffs are discussed along with operational considerations, cost, and availability of commercial equipment.

II. Dilatometer Design and Performance Requirements

A high precision dilatometer is being designed to achieve the following performance criteria: operation over the temperature range from ambient to 800°C, in a vacuum or inert gas atmosphere, with a sample length change measurement sensitivity of ten microinches (2.54×10^{-4} mm) or less. For a one inch sample and a temperature range of 1000 K, this sensitivity corresponds to a measurement precision of the mean thermal expansion coefficient of $\Delta L/(\Delta T) \sim 10^{-8}/K$. The dilatometer should be operational for a variety of sample types over a wide range of expansions, at least from $10^{-4}/K$ to $5 \times 10^{-7}/K$. While such a dilatometer would be useful as a research laboratory instrument, a number of additional requirements are desirable for measurements in a production environment. First, both sample size and shape should be non-critical, in order to minimize sample preparation time. Second, sample measurement time should be minimized. In addition, the design should incorporate features which allow the greatest ease of operation, with a minimum of set-up time. Critical alignment should be minimized, or automated if possible. Automatic data acquisition and reduction should also be used. In short, for a quality control application, the dilatometer design should allow high precision thermal expansion measurements to be made on a routine basis.

III. Survey of Interferometric Dilatometry

Although several techniques exist for high precision dilatometry, the technique employing laser interferometry is attractive for several reasons. First, the method is inherently precise, as it uses the wavelength of laser light as the length measurement standard. The ultimate limitation to the precision is

the uncertainty in the laser output wavelength. Second, the interferometric technique is a "non-contacting" method, in that the length measuring probe does not thermally contact or perturb the sample. This eliminates many of the problems which are present in thermally-contacting (e.g. push-rod) techniques. Third, the measurement is absolute, not relative to the expansion of a reference material. Finally, there is considerable experience available in the technical literature, indicating feasibility of the method and offering several possible technical approaches. Basically, these technical approaches can be divided into two major categories, depending on the optical interference method employed.

A. Multiple-beam Interference

The most common techniques used for dilatometry are multiple-beam interference methods, which are known by various phrases including "Fabry-Perot" and "Fizeau" methods (Figs. 1 and 2). Basically, they consist of forming an optical resonant cavity between two reflecting surfaces. Successive reflections from the optical elements which form the cavity interfere constructively or destructively, forming interference fringes. The resultant fringe pattern, viewed in either transmission or reflection, results from the spacing of the optical elements. Typically, the sample forms the cavity spacer; upon thermal expansion, the cavity spacing changes, leading to motion of interference fringes. The detection of this motion yields the change in cavity length. In fact, an ASTM standard test method [1] uses the Fizeau method for thermal expansion measurements of rigid solids. Fused silica optical flats (uncoated) are used as the reflection surfaces. Expansion can be measured absolutely, or relative to standard materials.

T. Hahn [2] at NBS has reported use of a Fizeau interferometer (using an incoherent light source) for expansion measurements of standard reference

materials (SRM's) to 700 K, with an estimated uncertainty of $\pm 3 \times 10^{-8}/\text{K}$. Amatuni and Mal'yutina [3] in the Soviet Union report the use of a similar arrangement to 1500 K (no data available), with a quoted standard deviation over a 100 K range of $\sim 7 \times 10^{-8}/\text{K}$. It is generally conceded that, for precision measurements, a series of isothermal holds is preferred to a temperature ramping technique [3,4]. Typically, a temperature ramp of 1-3 K/min is the upper limit, above which the optical alignment is frequently upset. For a series of isothermal holds, it would be extremely difficult to measure two samples per day. Hahn [4] reports about two days per sample, with a large time spent allowing temperature to equilibrate for each point. Even ramping the temperature, he suggests that one sample per day may be the limit.

W. Plummer at Corning also uses a Fizeau interferometry method and has reported measurements to 130°C with a precision $\Delta\ell/\ell \sim 10^{-7}$ [5]. He uses a He-Ne laser source and dielectric-coated optical flats in the optical-sample cavity. A He-Ne laser Fabry-Perot dilatometer was used at Kirtland AFB, for temperatures to 300°C [6]. Fringe interpolation was used which could detect sample expansions $\sim \lambda/40 = 0.016 \mu\text{m}$ ($= 0.64 \mu\text{in}$).

An ultra-precise method for thermal expansion measurements has been reported by Jacobs *et. al.* [7], over the temperature range 0-300°C. Their measurements employ a Fabry-Perot etalon; by imposing frequency sidebands on the laser line, and observing changes in the frequency domain, they quote accuracies limited by laser frequency stability, about 1 part in 10^9 . A similar technique was used by Foster and Finnie [8] to measure small thermal expansion coefficients on materials to 40°C with an accuracy of $\Delta\ell/\ell \sim 4 \times 10^{-7}$. They piezoelectrically modulated the frequency of a single-frequency laser and observed transmission through the Fabry-Perot etalon formed by the sample, rather than using the more standard fringe-counting technique. A recent extension of this technique to 300°C has been reported from the Soviet Union [9].

The two primary advantages of the multiple-beam interference method are its high precision and a partial immunity to environmental perturbations (thermal and otherwise) on external optics, since the interference occurs within the optical cavity, inside the heating chamber. The method has, it appears, three major drawbacks. First, extensive sample preparation is necessary [4,10]. Depending on the method used, sample size and shape restrictions may be severe. For example, the design shown in Fig. 1 uses three samples, of precisely equal length and a shape to permit the tripod support of the upper optical flat. The design shown in Fig. 2 uses a hollow cylinder sample shape, with ends highly polished and parallel. Second, fringe counting techniques may be difficult to automate, since polarization techniques cannot be employed. The frequency-modulation techniques, while extremely sensitive, do not allow bidirectional (phase quadrature) counting techniques necessary to distinguish expansion from contraction. This in turn necessitates slow temperature ramping rates, and thus long measurement times. Finally, for temperatures in excess of 300°C, suitable reflective optical coatings may be difficult to achieve and maintain. (At least one of the optical elements in the cavity must also be partially transmitting.) To some degree, this is a disadvantage to any interferometric technique and represents a problem which must eventually be overcome.

B. Double-beam Interference

A number of optical dilatometers utilize double-beam interferometry. These techniques all employ versions of the Michelson interferometer, shown in Fig. 3. In this arrangement, fringes are formed at the detector by the interference of wavefronts from the two optical paths. Motion of either mirror changes the optical path length of one beam relative to the other, resulting in fringe motion. By designing the dilatometer so that thermal expansion of the

sample causes motion of a mirror in one of the optical legs, the resultant fringe motion indicates sample elongation or contraction.

Double-beam interferometers have a sensitivity which is limited by accuracy of fringe interpolation. Using bidirectional electronic fringe counting (see [11]) an electronic "count" is generated for each displacement of $\lambda/8 = 0.08 \mu\text{m}$ ($= 3.1 \mu\text{in}$). More sophisticated fringe interpolation techniques have also been employed. With a double-beam interferometer, polarization coding techniques can be used to generate the phase quadrature signals used for bidirectional fringe counting. Such techniques are generally very reliable and versatile.

A double-beam interference dilatometer has been built by Roberts [12] for use on metals to 1000°C with a sensitivity of $10^{-8}/\text{K}$. He uses metallic reflecting samples lapped to $\lambda/10$, and a polarization interferometer with a laser source. E. Wolff [13] at Aerospace has developed a double-beam interferometer for measurements on low thermal expansion materials to about 400°C . Through a careful precision analysis and sophisticated fringe interpolation, he claims a length change resolution of 4×10^{-8} in. Cezairliyan and Miller [14] are currently developing a double-beam interferometer for measuring thermal expansions of metals, transiently heated to 2000°C and above.

While double-beam interference methods offer inherently less precision than their multiple-beam counterparts, they do have some advantages, most notably reduced sample preparation. In a double-beam technique, either one or two (opposing) surfaces of the sample are used as the mirror. While there may be extensive sample preparation necessary for cutting, polishing, and possibly coating the sample, the requirement for strict control of either sample shape or overall size is removed [15]. For polished metals or coated specimens, the sample is not in contact with any other material (except support) [12,13]. This "contactless" measurement thus allows arbitrary sample size and shape, reduces

problems of differential contraction and residual stress, and eliminates the need to find an optical-contacting method suitable at high temperatures. An additional advantage is that polarization techniques can be used for fringe counting.

A disadvantage of double-beam interference methods is that, depending on the optical arrangement of the interferometer, alignment of the optical components may be difficult. This problem can be reduced to some extent through improved optical design, although this is a problem common to any method which employs optical interference. Both interference methods may require slow temperature ramping rates to avoid optical misalignment. This reflects the fact that high precision and speed of measurement are often mutually exclusive.

While this survey is by no means exhaustive, it is representative of the methods which have been employed, and indicates the temperature ranges and precision of work by other researchers. There is an apparent scarcity of data for temperatures above about 400°C; in light of the need to reach the 600°-1000°C regime, this may be of some concern. There are several probable reasons for the lack of high temperature interferometric dilatometry data. First, much of the literature describes work done for a particular material or application, where the need for expansion data is limited in temperature. An example is the work of Wolff at Aerospace; he defines the "aerospace working range" as $0 \pm 200^\circ\text{C}$ [13]. Another limitation to the temperature range is the restriction due to optical coatings. Reflective coatings may seriously degrade, either optically or mechanically, above 400°C; currently, this is an unknown. For multiple-beam techniques, some researchers found that uncoated optical flats give adequate results; for double-beam methods, a surface(s) with enhanced reflectance will undoubtedly be necessary. A third reason that many researchers have not worked

at high temperatures may be related to their need for highly accurate thermal expansion coefficient (i.e., derivative) data. For example, if the temperature uncertainty is 1°C over a 100°C temperature range, then the resultant precision of the expansion coefficient will be 1%, regardless of the precision of the length change measurement. Above 400°C , thermal gradients in samples can be appreciable; Wolff cites this as a reason for limiting his working range to 400°C [15]. The existence of some data to temperatures near 1000°C indicates technical feasibility, although reaching temperatures of 600 – 1000°C on a routine basis will definitely present many technical challenges, and perhaps some loss of measurement precision.

IV. Technical Design

A. Optical Interferometer System

In view of the advantages and commercial availability of a two-frequency double-beam laser interferometer system (see Appendix I), and relative difficulty of sample preparation for multiple-beam interferometers, the double-beam interference technique appears to offer the best optical design for the dilatometer. Using the Hewlett-Packard (H-P) laser interferometer (see Appendix I), both the laser control and fringe counting apparatus are completely self-contained in an operable system, saving much development time. This interferometer system uses a two-frequency laser to achieve heterodyne frequency mixing of the phase information in each optical arm of the double-beam interferometer. This technique allows ac detection of the fringes in the frequency domain, and has several advantages over conventional dc (single frequency) fringe counting techniques. The output of the He-Ne laser consists of two frequencies f_1 and f_2 , separated by approximately 2 MHz , and coded by their orthogonal linear polarizations (see Fig. 4). The two frequencies are split into the two optical

paths ("stationary" and "moveable" mirror) by a polarizing beamsplitter and quarterwave retarders, so that each optical path in the furnace represents a single frequency of laser light. Upon recombination at the beamsplitter, the two frequencies are now phase shifted by Δf_1 and Δf_2 due to motion of the mirrors in the furnace. The H-P laser system detects the return beams and extracts the phase shift to generate the difference in motion between the two reflecting surfaces.

Aside from representing a newer technology, a laser light source is desirable for several technical reasons: 1) frequency and power stability, 2) better fringe visibility, 3) monochromaticity yields less wavelength uncertainty, and 4) the long coherence length of a He-Ne laser allows for large differences in optical length within an interferometer, which in turn means that sample length is virtually unrestricted. A possible disadvantage of the H-P laser system is its relatively low laser power output, nominally 100 mwatts. Special selection of a higher output plasma tube can be made during ordering; the development system in this laboratory has an output in excess of 230 mwatts.

Additional optical components and specialized coatings can be obtained from a number of sources.

B. Sample Configuration

Two possible sample measurement arrangements are shown in Figs. 4 and 5, along with the optical schematics. Basically, the two optical paths are necessary to separate true sample expansion from uniform translational motion of both sample and support. The main advantage of the horizontal sample arrangement (Fig. 5) is that sample mounting fixtures, furnace, and external optics can be located on a single table level. This allows for somewhat easier construction, and, since the optical beams remain in a single horizontal plane, air convection effects

on the beams are reduced. From many other considerations, however, the vertical arrangement (Fig. 4) appears superior: 1) easier sample preparation (two parallel faces vs a sample with parallel faces prepared perpendicular to the sample axis); 2) less difficult mounting of mirrors onto the sample; 3) easier optical alignment; 4) both beams pass through the same windows and atmosphere, requiring little correction (if any), while in the horizontal design, only one beam (f_2) passes into the furnace (twice), requiring a doubling of the corrections for pathlength; 5) easier vacuum connection; 6) much fewer beam-bending optics (each adds to loss of the signal); and 7) less disparity between the two beam signals.

C. Sample and Support Mirrors

Several conceivable mirror arrangements are possible; three are shown in Fig. 6. In 6a), a correction is needed for the expansion (known or measured) of the first-surface mirror mounted on the sample. In 6b), this correction is made automatically, if both mirrors are of the same dimension, material, and at identical temperatures. The assumptions of identical material and dimensions made in 6b) are irrelevant in 6c), where second-surface mirrors are used. Such mirrors may also have superior optical properties after several thermal cycles. Combinations of first- and second-surface mirrors are also possible. Metallic samples may require no additional mirrors if properly polished. Suitable reflective coatings (dielectrics, Pt, Au, Ir, etc.) may be evaporated or sputtered directly onto samples or re-usable mirrors. Sample dimensions in our experiments are approximately 1 cm diameter cylinders, 2 cm long; however, these dimensions are non-critical.

D. Atmosphere

For ease of set-up, an air atmosphere would clearly be simplest. However, oxidation of metallic coatings, thermal effects on exterior optical components,

and sample thermal uniformity, probably force the use of a closed system, either a rough vacuum or gas. For a gas atmosphere, a correction is necessary for the temperature-induced change in optical pathlength. Turbulence or gas density gradients may also cause errors. The use of a slight pressure (1 Torr) of He gas may offer improved thermal response and uniformity over a vacuum, without affecting the refractive index.

2. Furnace System

The furnace system is designed around the use of a quad-elliptical radiant heating chamber, manufactured by Research, Inc., Minneapolis, MN. The split-shell design affords easy access to the sample area in a vertical configuration. The extremely low thermal mass of this furnace offers rapid response and cool-down, thus improving sample turnaround time. This response is at the expense of some thermal uniformity, relative to a resistive, tubular furnace. Again, one is faced with the tradeoff between measurement speed and ultimate precision. However, the low thermal mass has the additional advantage that thermal disturbances in the atmosphere around the furnace and at the optics are minimized, thus greatly improving interferometer stability.

Vertical temperature gradients in the sample will be determined through experimentation, and may be as high as $2^{\circ}\text{C}/\text{cm}$ on samples at 600°C . The difficulty here will be in reducing the vertical gradients without appreciably adding to the thermal mass of the system. Three temperature measurement probes will be examined for use in the dilatometer: (1) platinum resistance thermometry (Pt RTD), (2) platinum/platinum 100% rhodium thermocouples (type S), and (3) chromel/alumel thermocouples (type K). With calibration, one can expect accuracies on the order of $\pm 0.1^{\circ}\text{C}$, $\pm 0.5^{\circ}\text{C}$, and $\pm 1^{\circ}\text{C}$, respectively, for the three probes. Temperatures above 650°C may preclude the use of Pt RTD probes. Tradeoffs between temperature measurement precision and ease of sample fixturing will

be examined during development; the latter is affected by the type of temperature probe, the location of the probe, and the mounting technique used.

A complete dilatometer system is shown in block diagram in Fig. 7. Both sample elongation and temperature can be recorded by an automatic data acquisition system. Thermal instrumentation can include both thermocouple and platinum resistance thermometry. Microprocessor control of all temperature programming will be used. Approximate cost information is presented in Appendix II.

V. Operational Considerations

A. Modes of Operation

Sample turnaround time will influence the actual mode of operation of the dilatometer. As in push-rod dilatometry, one mode of operation would be to collect elongation data during ramping of the sample temperature. The resultant data Δl vs temperature gives the total elongation over the temperature range, which can be differentiated to give the linear thermal expansion coefficient vs temperature. Typically, data are obtained with various ramp rates in order to observe systematic errors.

Optical interferometry, however, requires very critical alignment. For example, the optical beams from the H-P laser are about 1 cm in diameter. To achieve wavefront interference of one fringe (or less) over this diameter requires that the beams be parallel to within approximately ten arc seconds. Hahn [4] estimates a limiting ramp rate of 3K/min in a typical system, which severely limits sample turnaround. Using interferometry, only length changes are measured; thus, Δl data can only be accumulated during sample heating or cooling. However, heating too rapidly can cause disruption of the optical alignment by inducing tilt due to non-uniform expansion of the sample or its

support. If alignment is upset during ramping, the fringes disappear, and the sample elongation data (referenced to the sample length at the beginning of the run) is lost.

Another mode of operation consists of ramping the temperature between several isothermal holds; this is generally considered the more precise method for data accumulation. Again, optical alignment during temperature ramping must be maintained to collect ΔL data over the entire temperature range.

A third mode of operation, which is not apparent from experience with push-rod dilatometry, may offer some advantage for interferometric dilatometry. The method involves rapid temperature ramping between isothermal holds, with possible optical misalignment. At each isotherm, one regains optical alignment, and ramps the temperature (slowly) in the region of the isotherm. The resulting data give a mean thermal expansion coefficient at this temperature. The expansion coefficients at several temperatures can be curve-fit to establish either an average thermal expansion or the total sample elongation. (This method would incorrectly be applied to materials with discontinuities in ΔL vs T ; such samples could be readily identified by push-rod dilatometry.) Thus the method offers both reduced sample measurement time and the precision of optical interferometry.

B. Discussion of Errors

The ultimate precision of the length-measuring apparatus is determined by the resolution of the interferometry system, which is one microinch. Such precision is likely reduced by at least a factor of ten due to external perturbations on the interferometer. Measurement reproducibility will be determined by experiment.

Sample temperature gradients or uncertainty may be the limiting factor to measurement precision. If temperatures can only be determined to a precision of

one percent, the thermal expansion coefficient will have one percent precision, regardless of the length-measurement precision. As an example, consider a one inch sample with expansion coefficient $5 \times 10^{-6}/K$, measured over a temperature range of 600 K. A precision of $\Delta L \sim 50$ microinches and $T \sim 1\%$ corresponds to a thermal expansion coefficient precision $\sim 10^{-7}/K$.

Various corrections may be necessary for the dependence of the laser wavelength on ambient air temperature, pressure, and relative humidity. Such corrections are compounded if the sample is in a heated gas atmosphere.

Since the length determination is an absolute measurement, routine calibration is unnecessary. Comparison to expansion of NBS Standard Reference Materials (fused silica, copper, etc.) will be used during instrument testing.

VI. Conclusion

This study outlines several design criteria for a high precision dilatometer employing laser interferometry. The use of a modified Michelson double-beam interferometer appears to be the better choice of optical design. The length measurement system will be based on such an interferometer, using a two-frequency He-Ne laser, and heterodyne frequency mixing and ac detection for the fringe counting system. A vertical sample/furnace configuration offers a number of design advantages over a horizontal arrangement. While speed of sample measurement and high precision are often mutually exclusive, a particular operational mode of the dilatometer may achieve both. The dilatometer should be capable of determining mean thermal expansion coefficients to a precision of $1 \times 10^{-7}/K$.

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Appendix I. Commercially-Available Interferometry Equipment

There is apparently only one manufacturer of a complete interferometric dilatometer system [4,10]: Gaertner Scientific Corporation, Chicago, Illinois, makes a dilatation interferometer for thermal expansion measurements on small samples from room temperature to 1000°C. The system uses a Fizeau interferometer (Fig. 1), illuminated by an incoherent light source. In standard form, expansion is observed visually (through an eyepiece) by counting fringes which pass a reference mark. The furnace is a vertical tubular furnace, resistance type. Three samples must be prepared to support the top optical flat; the flats are uncoated fused silica. The basic dilatometer (includes furnace, control, sample supports, Hg source, fringe viewing apparatus) is \$6.5K. Gaertner can also equip the system with an automatic fringe monitor for an additional \$5.6K. This device consists of optics and electronics to record fringe motion (varying light intensity) on a strip-chart recorder (not included). Discussions with Gaertner reveal that a system was once sold with modification for a laser source; additional details (cost, performance, etc.) are not available. A user of a Gaertner dilatometer [16] at NASA Langley described the system as difficult to set up and not state-of-the-art even several years ago.

Theta Industries, Inc., Port Washington, NY, is currently developing an interferometric dilatometer for the range 77K to ambient temperature. This system will reportedly use a He-Ne laser light source, the Fizeau interferometric technique, and bidirectional fringe counting.

Hewlett-Packard manufactures a complete laser interferometer system. This system is specifically designed for use during set-up and calibration of machine tools for length accuracy, flatness, straightness, etc. As such, the system has been designed for use in non-ideal environments (smoke and noise) by technicians unfamiliar with its underlying operating principles: the system is effectively

a "black box." The H-P laser interferometer is essentially a double-beam instrument. External to the H-P system, one simply provides a mirror surface to redirect the laser beam back into the system. A digital display reads out the mirror position to the nearest microinch. The operating principle of this device uses a two-frequency mixing technique which allows ac detection. This makes the system highly immune to, e.g., air turbulence and thermal gradients along the beam path. The device can reportedly tolerate a 95% loss of beam intensity without losing counts. There are at least two H-P laser interferometer systems at Sandia Laboratories, Albuquerque. The device is very simple to operate. The digital output allows natural incorporation into an automatic data acquisition system.

The basic cost of the H-P laser system is \$12K, which includes the frequency-stabilized laser, photodetection system, electronics, and digital display. Optical components exterior to the laser depend on the specific interferometer arrangement, and must be supplied additionally. Purchased from H-P, optical components could easily total \$10K, while components from other suppliers would be ~\$3K. Part of the H-P cost is because their components are mounted in metrology-grade gauge blocks with necessary study mechanical design. For an additional \$10K, the laser system is interfaced to an HP 9815A calculator for data acquisition, and to an X-Y plotter for display.

The HP laser system contains two independent detection systems, so that, for an additional \$5K for the electronics and laser display, two interferometers could be operated (in principle) simultaneously. This would allow operation of two furnaces, should sample turnaround be a problem with one.

Appendix II. Development Cost

The following tabulation represents approximate equipment development costs, based on expenditures to date (Sept. 1, 1978) and anticipated future costs.

	<u>\$(K)</u>
Laser Interferometer System	12.0
Furnace System	4.6
Optical Table	4.5
Optical Components	8.9
Optical Mounts	5.1
Electronic Instrumentation	9.2
Vacuum System	3.0
Technical Support	4.0
Miscellaneous	<u>2.0</u>
	\$53.3K

One of the difficulties with projecting the cost of a complete dilatometer system, after development, is the uncertainty of the type, sophistication, and cost of the data acquisition system. One can envision a spectrum of devices, ranging from relatively inexpensive (~\$1K) microprocessor-based data acquisition, to a calculator-based system (e.g., the Hewlett-Packard 9825A), which could be used for automatic control as well as data acquisition, analysis, and presentation. Such a system could cost as much as \$15K. The following table lists the approximate anticipated cost of a complete dilatometer system, with the exception of the data acquisition system.

	<u>S(K)</u>
Laser Interferometer System	12.0
Furnace System	5.0
Optical Table	4.0
Optical Mounts & Components	5.0
Instrumentation	3.0
Vacuum System	3.0
Technical Support	<u>4.0</u>
	\$36 K

FIZEAU INTERFEROMETER

Figure 1. Sample configuration using Fizeau interferometry.

Figure 2. Sample configuration using Fabry-Perot interferometry.

Figure 3. Schematic optical design of a Michelson interferometer.

Figure 4. Vertical sample/furnace configuration. The optical design incorporates a two-frequency laser.

Figure 5. Horizontal sample/furnace configuration. The optical design incorporates a two-frequency laser.

Figure 6. Possible sample configurations using double-beam interferometry.

- a) Two first-surface mirrors.
- b) Two first-surface mirrors. Expansion of sample mirror is cancelled by elongation of reference mirror.
- c) Two second-surface mirrors.

LASER INTERFEROMETRIC DILATOMETER

Figure 7. Block diagram of a complete laser interferometric dilatometer.