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HIGH TEMPERATURE STRAIN MEASUREMENTS USING DIGITAL OPTICS

RANDY R. NIELSEN
TERRATEK, INC.
420 WAKARA WAY
SALT LAKE CITY, UTAH 84108

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Charles R Henderson

Lt Charles Henderson, Project Engr
Fatigue, Fracture and Reliability Section

Anthony S. Lizza

ANTHONY S. LIZZA, Technical Mgr
Fatigue, Fracture and Reliability Section

James L. Rudd

JAMES L. RUDD, Chief
Structural Integrity Branch
Structures Division

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Randy R. Nielsen

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Terra Tek Inc
University Research Park
400 Wakara Way
Salt Lake City UT 84108

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Kevin L. Boyd (513-255-6104)
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Current methods used to measure strain at high temperatures depend on undesireable attachments or indentations and are generally limited to temperatures below 1800°F. The objective of this effort is to develop, construct, and demonstrate an ultrahigh-temperature strain measurement system using unobtrusive thin material coatings applied to test samples as reference marks for optical strain monitoring. The contents of this report describe the development of a system capable of measuring strain on specimens at temperatures ranging from room temperature to above 2000°F.

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I. INTRODUCTION

Determining mechanical properties at extreme temperatures (> 2000°F) has been a most difficult problem. Standard techniques, such as strain gauges or transducers (that use strain gauges), to measure strain are severely limited by temperature. "Conventional" (high temperature) strain gauges can measure strain up to about 600-650°F. However, special gauges applied using "flame spray" techniques (feral alloy) are accurate to about 1500°F. Extensometer type strain transducers (with quartz or ceramic rods) can measure strain at applications to 1800°F (quartz) or 2200°F (ceramic). These methods that thermally isolate typical transducers from heated test samples introduce numerous additional problems and uncertainties to the measurements. To provide measurements of strain, the transducer must contact (be attached to) the sample within the gauge section of the test sample. These attachments effect the temperature distribution at the point of contact, and alter the stress-strain response at that point. The accuracy of any attachment is always a concern. The more extensive the efforts to prevent slipping, the larger the possible effects on over-all accuracy. For materials at or near melting or ablation temperatures any contact with the test sample is an undesirable and often unacceptable complication.

Current technology allows some stress-strain measurements to be performed at temperatures up to 5000°F using optical techniques. In fact, these services are available at commercial laboratories in the United States. Techniques were developed over 15 years ago at the General Motors Materials and Structures Laboratory to measure strain on high temperature materials at ablation temperatures[1]. Optical tracking or gauging systems such as those manufactured by Optron or Physitech were able to provide accurate measurements of strain, but the most difficult problems then, as now, is that of providing a suitable marking or reference system to look at and a method and equipment that are simple and straight forward to use. Optical methods have the advantage of being non-contact, but require that visual gauge points be used as references. Methods that incorporate shoulders or mechanical notches fabricated into the specimen often suffer from the obvious and often severe limitation of introducing stress concentrations into the specimen. This problem could be alleviated by depositing thin gauge marks of a second material on the specimen to act as the optical reference. Currently, improved optical methods using laser speckle or moire fringe patterns are available, but speckle or fringe patterns tend to be more difficult to use and interpret as compared to typical transducers.[2]

A method that combines the advantages of optical measurements without the disadvantages of shoulders or notches or the complexity of speckle or fringe patterns would obviously enjoy wide application. Such a method depends on the successful application of gauge marks. Several critical research problems arise in the production of gauge marks. Materials must be used that will have negligible or, at most, little effect on the properties of the part whose strain state is to be measured. The gauge material must be stable at the temperatures and in the environments of interest for the tests. The optical properties of the gauge material must be sufficiently different from the host sample material throughout the test as to be discriminable by the optical measuring device. Means must be developed to apply the gauge material in coherent and adherent layers so as not to damage the specimen or to result in significant sample reinforcement.

Candidate materials for the gauge marks are precious metals, refractory metals and ceramics. Several metals could be explored depending on exact temperature and atmospheric requirements. Table 1 lists melting and boiling temperatures for several metals[3]. In addition to high metals, carbon in the form of graphite sublimes at temperatures near 7000°F in an inert atmosphere but reacts with oxygen at much lower temperatures.

Table 1. Melting and Boiling Temperatures for Several Metals.

Metal	Melting Temperature (°F)	Boiling Temperature (°F)
Iridium	4442	7934
Molybdenum	4748	8404
Niobium	4478	8564
Osmium	5477	7637
Platinum	3218	6917
Rhenium	5760	
Rhodium	3569	6692
Tantalum	5396	9689
Tungsten	6152	10022

The problem with all these "elemental" materials is that, with the possible exception of platinum and rhodium, they have high oxidation rates at temperatures below 2000°F. For moderately high temperatures (approximately 3000°F), Pt, Rh and their alloys appear to be attractive candidates since they can be used in oxidizing environments. As evidence for this latter fact, Omega Engineering, Inc. manufactures 20 and 32 mill Pt 6% Rh/Pt 30% Rh thermocouples that they recommend for maximum service temperatures of 3092°F without restriction to non-oxidizing atmospheres[4]. These conditions are for wires where some structural requirements must be met. In the form of deposited films, it might well be that these elements and their alloys might be used at even higher temperatures, since their melting temperatures are several hundred degrees higher than 3092°F. In some applications where very thin layers of material are applied, they may even prove to be usable above their melting temperature.

Where the test atmosphere can be limited to hydrogen or inert atmospheres or a vacuum (as simulations for parts to be used in space), the refractory metals are very attractive candidates. Reference 3 lists W-Re alloy wires of .010 inch diameters for use at temperatures up to 5000°F[3].

For temperatures approaching 4000°F in oxidizing atmospheres, ceramics are probably the only viable gauge material. Such ceramics as beryllium oxide (BeO), calcium oxide (CaO), magnesia (MgO), and zirconium oxide are manufactured into items with service temperature at or in excess of 4000°F[3,4]. Since they are already oxides, they should be stable in oxygen environments up to near their melting temperatures.

There are three promising methods of depositing the gauge materials. Zirconia, Pt, and Rh are available in forms that can be deposited by brushing. Upon heating, the carrier liquid is driven off, leaving the metal behind in a tightly adhering film. These very easily applied gauges should be usable up to approximately 3000°F. Somewhat related to these are the temperature indicating crayons, temperature indicating liquids, or temperature indicating pellets. These are applied to a part to indicate the temperature by a change in appearance (change in optical properties of luster) accompanying a phase change. For example, one manufacturer, Therm$_x$ of San Diego, California*, makes a series of such products for indicating temperatures in 3-degree increments from 100°F up to 3000°F. Such materials might be used as a gauge basis for temperatures up to this point.

All the metals, carbon, and ceramics could be deposited by appropriately masking the sample and using either sputtering or chemical vapor deposition. These have the advantage of being well-developed methods. A number of books describe these methods and the resulting products in some detail[5-8]. We will, therefore, only very briefly describe these techniques here.

*Reference 4 lists similar lines of products.

Sputtering is perhaps the most commonly used of the ion bombardment techniques for modifying surfaces. In this method, the target material(s) is bombarded by ions (e.g., Ar^+, Ne^+, Hg^+, Kr^+, Xe^+, He^+, N_2^+, N^+, and A^+, etc.) which, in turn, drive ions from the target material that are then driven by an electric field onto or into the surface of a second host material. Reference 3 lists several pages of sputtering yields for a variety of metals, semiconductors, carbon, silicon, alkaline earth, and compounds including ceramics. Not only can films of pure elements be formed by this process, but also alloys and compounds.

In Chemical Vapor Deposition, CVD, the film is deposited on a heated substrate by reduction of a gaseous compound containing the atom(s) of interest by a reactive gas. For example, WF_6 can be reduced by H_2 gas on a mandrel maintained at temperatures between 1000°F and 1800°F to produce large parts of pure tungsten. Again, the process is not restricted to pure elements. By adjusting the partial pressures of the compound gases, the temperature of the substrate, and other factors, alloys and ceramics with carefully controlled stoichiometry can be produced[6,7].

Clearly, a marking system that could be used without damage to the test sample, that could be applied easily on any type of material and in any arbitrary direction to allow strains to be measured in the direction of interest, and that could withstand the temperature requirements imposed, could greatly extend the capabilities of high-temperature material property measurements. If successful, many of the optical systems could be used directly to provide relatively simple and accurate strain data in any direction of interest.

The availability of a simple system that could be used on all materials would greatly improve the accuracy and flexibility of current methods. Marks could be placed on any material in any orientation. A portable system could be used to mark high-temperature components for field tests and monitoring.

This new technology would have direct application in many areas, including:

- High-temperature components for missiles,
- New materials for aircraft engines,
- Ablative heat shield materials,
- Supersonic aircraft components,
- General high-temperature laboratory testing, and
- New materials for ceramic turbine application.

As new high-temperature materials are developed, the ability to perform straightforward, accurate strain measurements at the temperatures of interest will become increasingly more important. Ultimately, a simple optical system could replace many strain-gauge type transducers in everyday room temperature research.

The purpose of this project was to apply new technology, specifically digital optics, to measure strains at extreme temperatures (to in excess of 2000°F). The technique developed uses a combination of a high-speed digital camera with a 3500-element linear photodiode array and an 80386-based computer with custom software. The system successfully measured large displacement (40%) to within 50 microstrain using a room temperature micrometer as reference. The system's ability to easily and correctly identify gauge marks at temperature above 2000°F was demonstrated.

Outline of the Digital Optics System for Strain Measurements

The system measures strain by tracking two horizontal gauge marks (thin parallel, horizontal lines placed on the test sample) and measuring their relative positional changes. The system works as follows:

1. Two thin (approximate 0.012" to 0.020" thick) lines are applied on the test sample. These lines (gauge marks) must be of a contrasting color, e.g., black lines placed on a light background or white lines on a dark background.
2. The camera and lighting system are arranged to image the gauge marks onto a photodiode array in the camera.
3. Custom software directs the computer to process the image and calculate strain. Figure 1 is a reduction of a typical computer screen print.

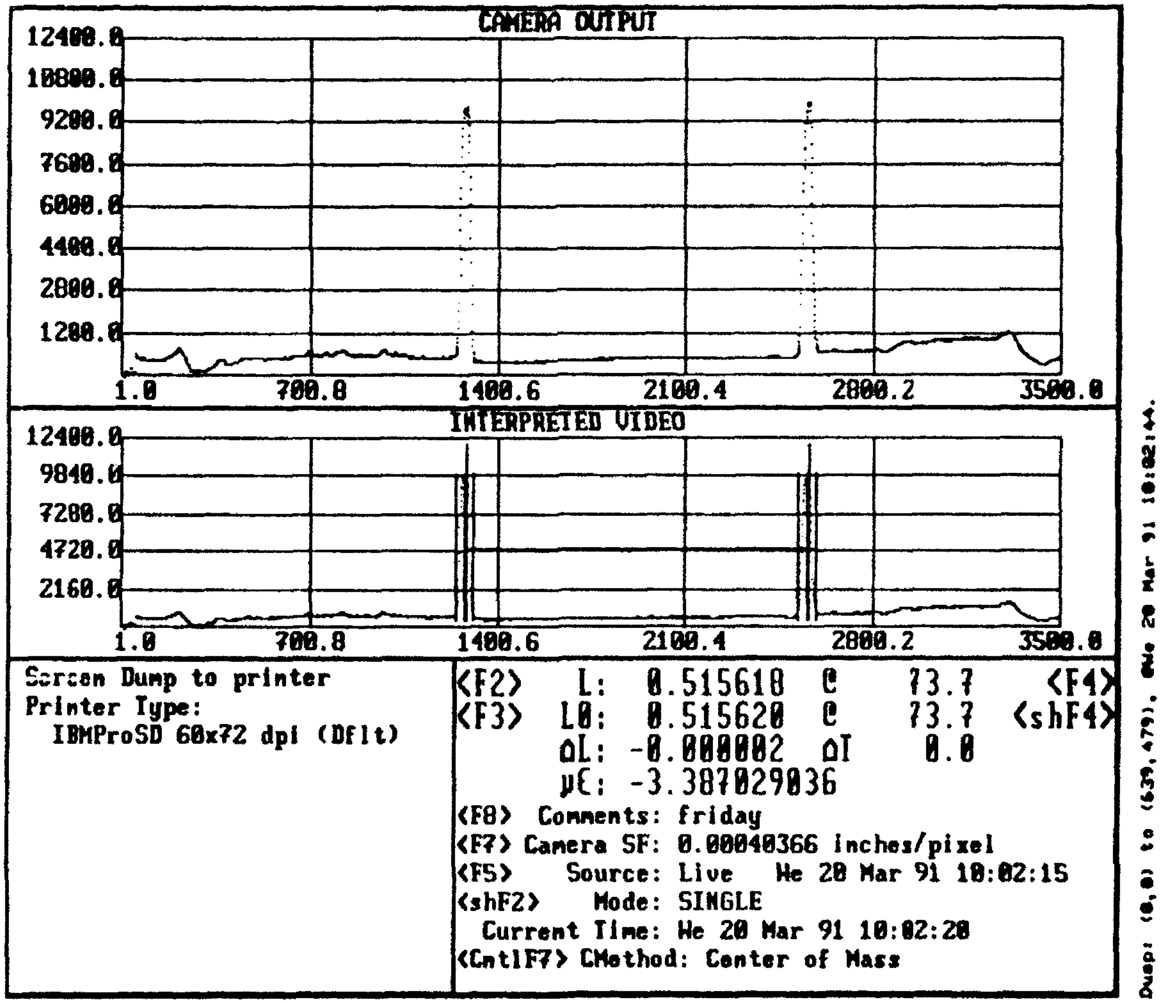

Figure 1. A typical camera scan of two gauge marks at room temperature.

This method and the equipment supplied are not limited to traditional laboratory applications. Theoretically, this system can accurately measure displacement on any sample or structure that can be appropriately marked. For example, gauge marks could be applied directly to structural members several feet apart. Given the correct lens, this system can measure the relative displacement of these members.

In some applications, gauge marks are not even required. Consistent readings were taken on a piece of material using two holes as gauge marks. The holes were lighted from behind. Parts that contain rivet holes or holes for some other reason could be tested using existing holes as references. It is likely that many other novel applications of this technology are possible.

There are many applications where, even though temperatures are not extremely high, strain gauges are difficult to use because of the need for wires, electrical brushes, or slip rings on moving parts. Some possible applications are:

1. Hot rocket parts during rocket testing.
2. Strains during high-temperature forming or other fabrication methods.
3. Strains in engines, turbines, or other machines.
4. General high temperature laboratory work.

In addition, this method lends itself to measurements on other hot or hazardous materials. Since measurements can be made through glass, without connection to a transducer, this method could be used for radioactive or toxic materials. With telescopic lenses, measurements could be made at distances remote from the test area, or an average strain could be measured for very large samples. If the system proved relatively inexpensive, it could even be used to monitor long-term strain on bridges and other structures.

II. EQUIPMENT

Detailed instructions for this equipment are included in the manufacturer manuals and the service videos provided. The brief descriptions provided in this section are intended to provide the technical basis for understanding the system operation. Figure 2 illustrates the version components that make up this system.

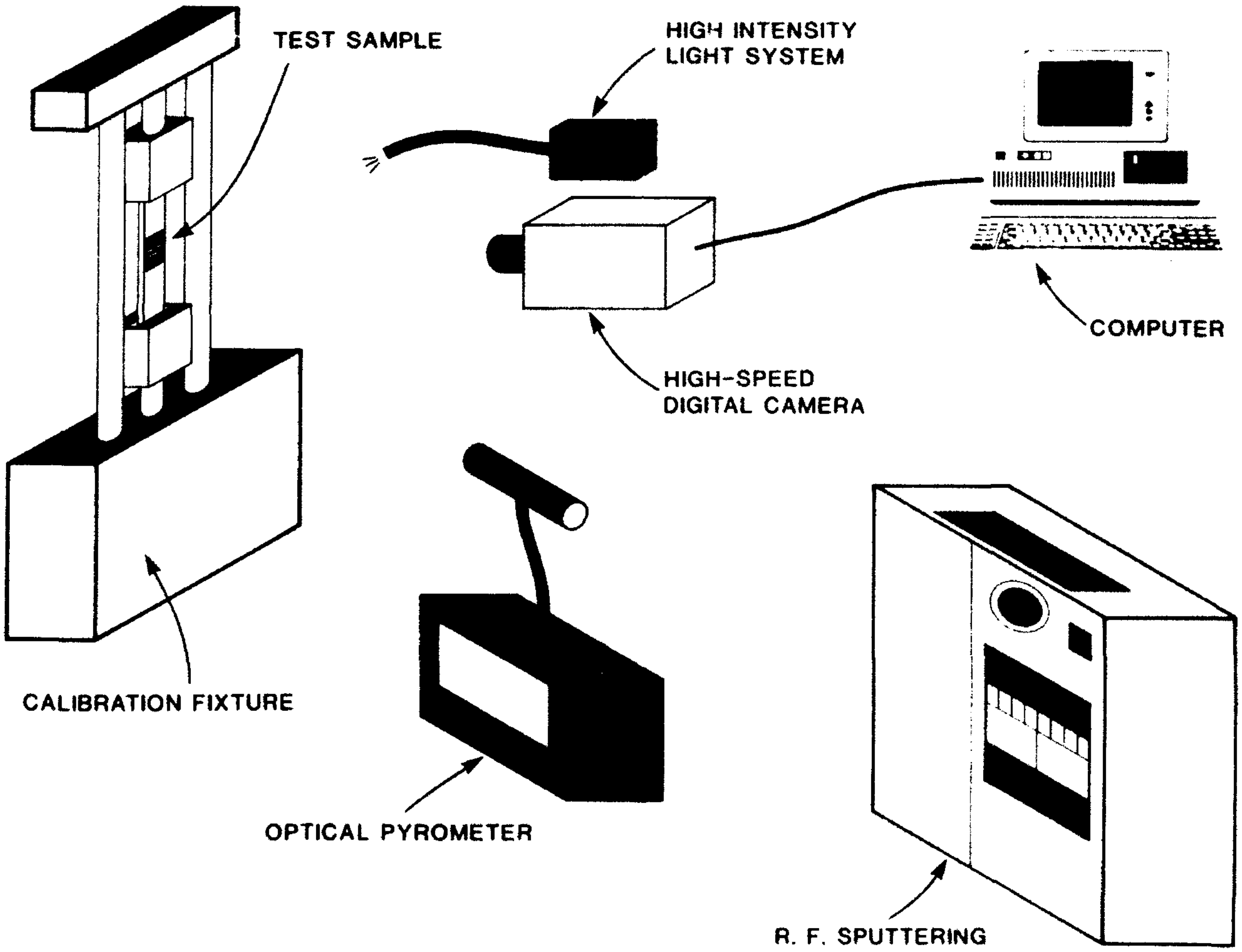

Figure 2. A schematic of the complete system.

Camera

The camera consists of a linear photodiode array. It is designed to use micro-Nikkor series lenses. For other applications (e.g., with camera further removed from the sample), other compatible Nikkor lenses are available. As delivered, the system is supplied with a 105-mm lens and extension tube providing for an optimum focal distance in the vicinity of 12 inches. To obtain optimum resolution, the gauge mark spacing should be adjusted to make use of a large percentage of the diode array. Even though the software allows a small portion of the camera's field of view to be projected on the output screen, better accuracy can be obtained by selecting lenses and gauge mark spacing that make use of the greater number of available pixels in the diode array. Lenses using higher magnification could be used to allow closer spacing of the gauge marks or larger distances between the camera and the test sample. Whatever the combination of lens, extension tube (if used), and gauge mark spacing selected, consideration should be given to make use of as much of the diode array as possible. The camera is clocked at 12 KHz. Limitations in the speed at which the computer can transfer and analyze data control the system response. The number of scans selected for averaging also effect the overall speed capability.

Lens Focus and Setting

The focus and "f" stop settings on the lens are critical for obtaining maximum accuracy with this camera. Simple trial and error experiments can be done during set-up that will greatly improve the overall results. "Ideal" samples are quite simple to measure. A sample, free of gloss with black background and with flat white gauge marks, can easily be seen by the camera. Furthermore, the gauge mark spacing can be readily measured.

More typical are metallic samples with discolored, dark backgrounds, but not black, that still have a metallic quality. Composite samples are often highly reflective. If these types of samples are illuminated directly, the glare from the reflection obscures the gauge marks. Such samples can be lighted from the side so that the reflected light is directed away from the lens. Closing the lens (using a higher f-stop) helps diminish the problem of reflections but also limits the camera output. By increasing the intensity of illumination along with closing the lens, the over-all quality of the image may be improved. By adjusting the level of illumination and the camera lens f-stop while viewing the camera output on the computer screen, it is possible to monitor the effects of the changes that are made.

Adjusting the lens focus can also greatly enhance the quality of measurements. A "through-the-lens" window is provided for camera alignment. The small lever above the window allows the sample to be viewed through the camera lens. The focus and placement can be adjusted. When testing the system, we noted that a very sharp focus was undesirable. Perfectly focused images reflect light from scratches and imperfections, and appear to the camera as very light colored areas. As a result, gauge marks can be obscured or misidentified (see Figure 3). An image slightly out of focus will diffuse spurious reflections eliminating or lessening the outputs caused by undesirable reflections. An unfocused image also smooths the gauge marks into bell shaped curves more easily analyzed by the software. Repeatability and accuracy are greatly enhanced by obtaining images that resembles smooth, continuous, curves.

Please note that changing the focus or the f-stop alters the image, affects the readings and should not be adjusted during a test.

Operating Software

The software directs the camera to scan the test sample, collects the individual voltage outputs from the 3500-element diode array, averages the readings from the array with other scans,

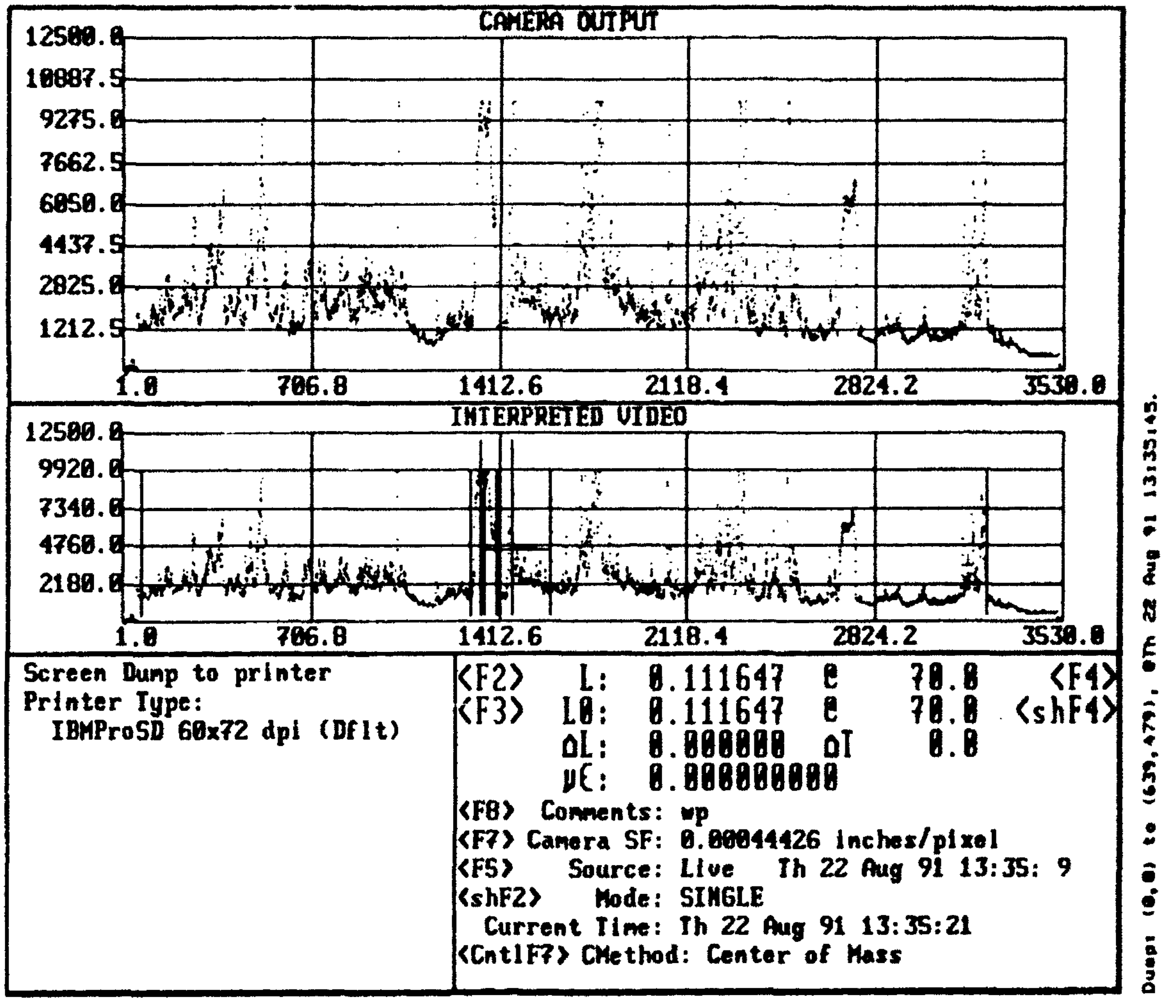

Figure 3. Results of a camera scan of a perfectly focused, directly illuminated reflective sample. The computer is unable to identify the gauge marks.

identifies the gauge marks, performs a mathematical fit of gauge marks and calculates displacement from the previous reading. The output from the camera is displayed on the computer screen. The software allows a zoom function to carefully inspect any part of any scan. The initial conditions are recorded (subject to operator reset and input) along with changes in temperature and strain. The software allows the operator to select the number of scans to be averaged (about 10 is optimum) and the type of mathematical model used to locate the gauge marks. Data files are provided to be used by the operator for the purpose of storing data.

Pyrometer

A Raytek Thermalert 5 optical pyrometer system, with two different temperature sensors (0°F to 1600°F and 800°F to 5400°F) is included with the system.

In summary, Thermalert 5 series instruments are infrared noncontact temperature measurement systems, including a rugged, sealed sensor head, detachable connecting cable, and electronics. The sensor head consists of optical elements, spectral filters, infrared detector, ambient sensor electronics, and rugged aluminum housing.

The electronics consists of A/D converters, two microprocessors, PROM, D/A converters, and power conditioners, all mounted in an enclosure designed for panel-mount or tabletop operation. The front panel of the enclosure contains a backlit LCD display and control switches. Inputs consist of sensor head signals, an external sensor signal, an external reset, and power supply voltage. Outputs consist of analog signals, relay contacts, and a digital RS232 C signal.

Specifications from the manufacturer's manual[9] are as follows:

Sensor Heads

Model	Temperature Range	Output
S5XLT	0 to 1600°F -20 to 870°C	Thermocouple: J,K,N Current: Selectable
S5XHT	800 to 5400°F 400 to 3000°C	Thermocouple: K,R,S Current: Selectable

Spectral Response:

LT	8 - 14 microns
HT	Nominal 2.2 microns

Accuracy:	±1% of reading or ±2.5°F (1.4°C), whichever is greater, @ 25°C ambient
Repeatability:	±0.5% of Reading, ±1 digit °F or °C

Operational

Response Time:	400 msec
Emissivity:	0.10 - 1.00, user adjustable
Set Point Range:	Full scale
Temp Ambient Range:	Full scale
Deadband Range:	0.1 to 50% of setpoint of ±2°F (1.0°C), whichever is greater. (0.1% increments from 0.1% to 1%; 1% increments from 1 to 50%)
Fail-Safe:	Full or low scale, user selectable

Electrical

Outputs:

Voltage

1 mV per degree (F or C)

Digital

RS232, one way, simultaneous with analog

Relay Contacts

SPDT contact closure (NO/NC)
Maximum 125 VAC, 60 VDC, 500 mA

Inputs:

External Reset

+5- to 25-Vdc pulse, min 600 msec minimum or contact closure

External Temperature

J,K,N,R,S thermocouples

Interconnection: 7 pin DIN connector cable, 25-foot (7M) standard

Physical

Ambient Operating Temp:

Sensing head	32°F to 150°F (0°C to 65°C)
With air cooling	32°F to 250°F (0°C to 120°C)
With water cooling	32°F to 350°F (0°C to 175°C)
Electronics Box	32°F to 120°F (0°C to 50°C)

Storage Temperature: -40°F to 150°F (-40°C to 65°C)

The pyrometer offers many advantages over alternative temperature measurement devices.

1. Like the camera system, it operates on optical principles, does not require contact with the sample, and can be used to measure through a high-temperature window.
2. The combination of the two systems has a very wide-temperature range (0°F to 5400°F).
3. The control and read-out unit is capable of several functions including heater control, recording and even graphical presentation of temperature data.

The accuracy of the pyrometer is highly dependent on sample emissivity and careful calibration. The emissivity can be calibrated easily using a thermocouple as a reference but for some materials the emissivity can change with the temperature. Be aware that if the sample surface is changing, errors in the pyrometer reading are possible. The effect can be observed by measuring the temperature of a metallic sample painted with high-temperature black paint. As the temperature is increased, the paint burns off, the emissivity decreases, and the indicated temperature (as measured by the pyrometer) drops. The accuracy of the system is also affected by measuring through a window. Some of the radiation is absorbed by windows and, hence, the pyrometer must be calibrated for the proper emissivity as measured through the window. The effects vary with the type of window material, the thickness and the wave length of the sensor. A technical bulletin addressing temperature measurements through high-temperature windows was obtained from Raytek and is included with the system manual.

In summary, care must be taken to insure that the pyrometer is properly calibrated for the actual test conditions. For exceptionally difficult setups a thermocouple can be used for reference. (The pyrometer electronics will accept thermocouple inputs.)

Calibration Fixture

A small hydraulic test frame, as shown in Figure 4, is provided to allow calibration and trial tests without tying up a full-sized test machine. The calibration fixture has tie rods of the same diameter (3 inch) and spacing (23 inches on center) as the full-sized test system at Wright-Patterson that will be used with the infrared oven. This will allow the high-temperature oven to be used as part of the trial tests on a smaller, more convenient scale.

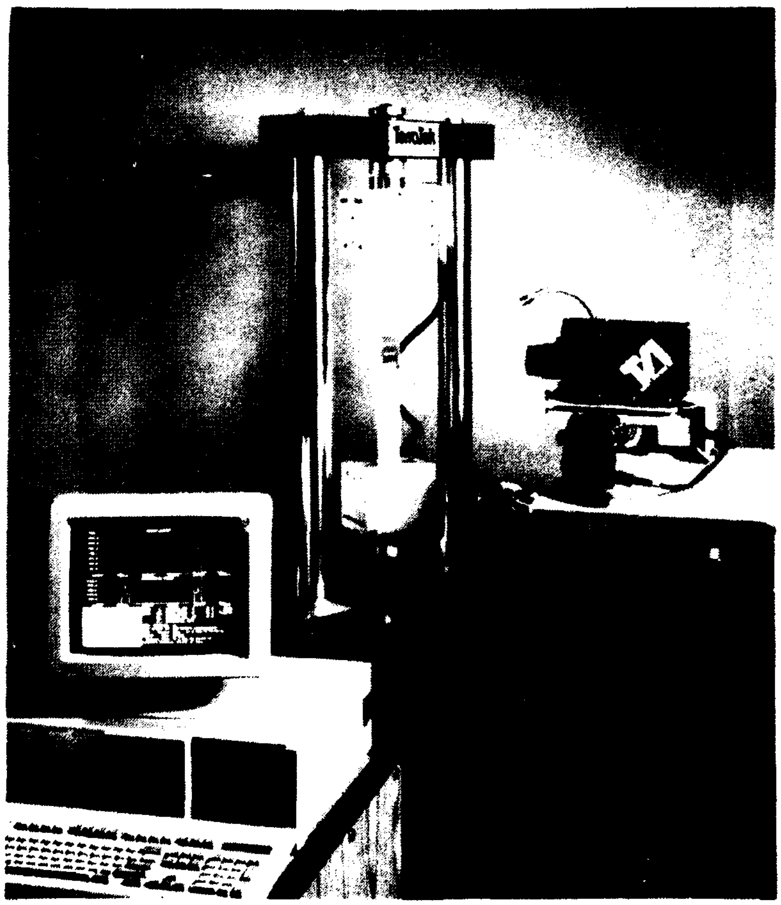

Figure 4. Photograph showing the high-temperature strain measuring system. The calibration fixture is in the center.

The calibration fixture has a design load capacity of 20,000 pounds, and is supplied with a load cell rated to 5000 pounds, the anticipated test load range during calibration. The lower grip has a total stroke of 6 inches. The adjustable top crosshead, powered by hydraulic lifts, has a range of 18 inches and is clamped with hydraulic locks. Simple hydraulic grips are also provided. The fixture uses 3000-psi hydraulics and a Dynamic Valves servo valve that will be compatible with existing hydraulics and control systems at Wright Patterson.

Radio-Frequency Sputtering System

Many techniques were used to coat samples in trial tests at Terra Tek. By far, the most versatile was the radio frequency sputtering system. This unit (Figure 5) has been provided to the Air Force under the present Contract. While a detailed operations manual is provided, some background information and technical observations for all of the techniques may prove helpful.

The goal of the coating experiments was to identify materials and processes that have general application to high temperature materials. Phase I tests showed that a gloss free, black background coated with low reflectivity white gauge marks would provide an ideal contrast for the camera. A low reflectivity surface serves to minimize undesired light reflections into the camera. (Bright reflections from the background are perceived by the camera as light colored areas and confuse the strain readings.) Ideal samples can easily be made with high-temperature engine exhaust system paint. This method is suitable for temperatures up to 1200°F for any material to which the paint will adhere.

Simple test samples for higher temperatures were prepared from stainless steel strips or stainless steel cartridge heaters. The material was first darkened by heating in the atmosphere to allow oxidation. Gauge marks were applied by hand using a water-based suspension of zirconia, brushed or sprayed onto the samples. The resulting gauge marks were not of excellent

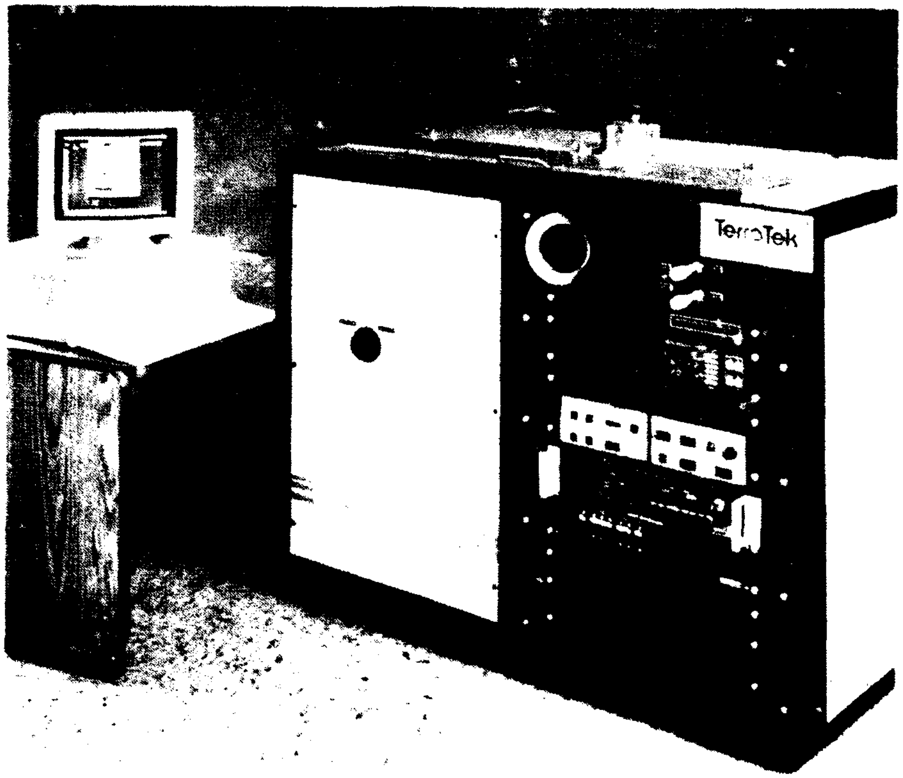

Figure 5. Photograph showing the radio-frequency sputtering system.

quality, but they were adequate to allow heating to 2200°F at atmospheric condition.

A radio-frequency sputtering system was selected for this project for many reasons:

1. A radio-frequency system can coat nearly any solid or powered material onto almost any substrate.

2. The coating is extremely thin and uniform--causing imperceptible changes to the substrate. The edges of the coating can be carefully controlled.

3. The coating becomes an integral part of the substrate

4. Reaction coating can be performed allowing oxides and nitrides to be deposited from elemental materials and oxygen or nitrogen bearing plasmas.

5. The process is well-developed and automated. Coatings can be performed with minimal difficulty.

During the course of this project, targets (the materials to be coated onto a substrate) of the following materials were obtained: copper, aluminum, zirconium, zirconia, magnesium oxide, molybdenum oxide, and carbon. Several different substrates were tried. Most of the coating was performed on common stainless steel sheet. The sputtering equipment was relatively simple to operate owing to a high level of automation.

Light colored, high-temperature oxides (such as MgO) were expected to be prime candidates for gauge marks. In applying Al_2O_3, MgO, and ZrO, the operator must be cognizant of the fact that those materials become transparent after coating. Figure 6 shows examples of transparent oxide coatings. The gauge marks can be seen by oxidizing the surrounding substrate.

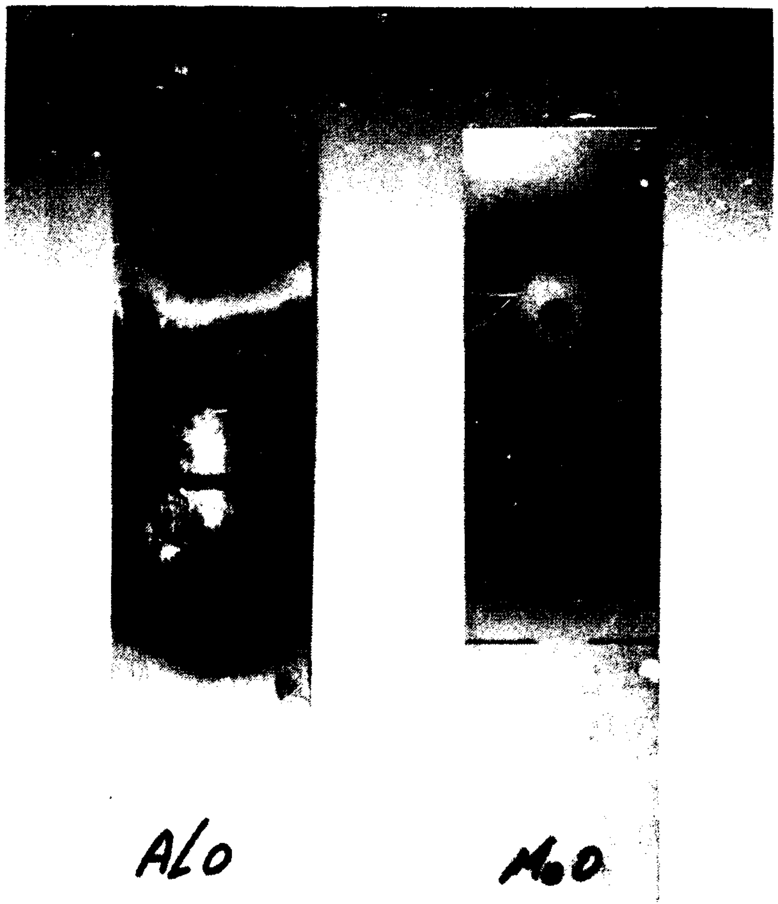

Figure 6. Photograph showing examples of transparent oxide coatings. The marks can be seen after heating the substrate and allow the surrounding area to oxidize.

Fortunately, high-temperature elemental metals (such as zirconium) can be coated easily and result in a silver coating (see Figure 7).

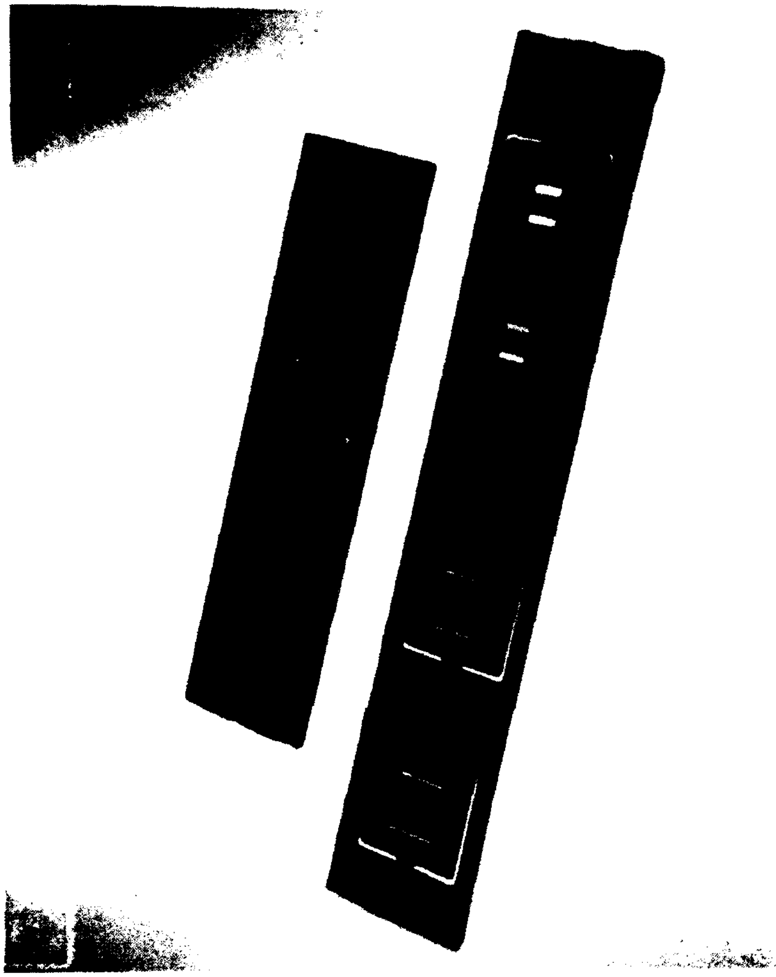

Figure 7. Photograph showing carbon and zirconium marks sputtered onto thermoset carbon composite.

III. EXPERIMENTAL RESULTS

The object and intent of trial tests at Terra Tek was to verify the accuracy of the camera system rather than to conduct meaningful research into the material properties of high-temperature materials. Information gained during the process can be helpful, and hence, the following observations are included for reference.

Camera Setup

The camera and lighting arrangement are critical for successful measurements. While there is no combination of settings that work best for every test, a good arrangement can be determined by varying focal length, camera alignment, lens focus and setting, light placement and intensity, and other variables. The best results are usually obtained by achieving a computer display of two well-defined, continuous, smooth "humps" representing the gauge marks with a uniform, low level output from the background. An arbitrary scale from 10,000 units down to negative numbers represents the relative intensity of the camera output as displayed on the computer screen. It is possible to saturate the diode array. This causes no damage to the system but it does lower the overall accuracy. If the humps on the computer screen are flat on the top at an intensity level of 10,000, portions of the array are saturated. Adjusting the camera lens for less light will put the display back in range. Accuracy is enhanced by having the camera output as high as possible from the gauge marks (without saturating the display) and as low as possible from the background.

Gauge Mark Width and Spacing

Wide gauge marks were not desirable for accurate testing. For example, gauge marks 1/8 inch wide result in a broad computer output that may not be symmetrical about the center of the mark. It may also appear to the camera as having two or more peaks across the top of a single gauge mark and hence, confuses the system and ruins the measurements. Marks as narrow as 0.015 inches were used and were found to work very well.

Optimum gauge mark spacing depends on the experiment to be performed. As with any transducer, accuracy is enhanced by using a reasonable percentage of "full scale." Allowance should be made for the maximum strain expected as well as the initial set-up spacing. A simple dummy sample (black paper with white pin stripe tape) will allow the proper spacing to be determined easily. Both the focal distance and the lens focus will effect the observed spacing of the gauge marks. The best accuracy will be obtained by using as much of the horizontal scale as possible.

Gauge Mark Deterioration

Since the camera scans a very narrow vertical line, camera readings are not affected by inconsistent gauge marks unless the scan intersects a portion of the gauge mark that is of poor quality or missing. Care should be taken during setup to align the camera with a good quality portion of the gauge mark.

Testing Rational

Measurements performed at room temperature, using a micrometer head to provide precise displacements, demonstrated the system's ability to accurately measure displacements at stable conditions. We devised a simple test to demonstrate the ability to measure displacements at temperature.

Gauge mark computer scans were recorded at temperatures up to 2200°F. The temperature conditions were neither uniform nor stable but the test did demonstrate the camera's ability to locate gauge marks to this temperature. The heating was supplied by a small oxygen-propane torch. Larger, hotter torches were not used to avoid potential flame damage to the camera and lighting.

Test Results - Room Temperature

Measurements at room temperature, made with a precision micrometer, are listed in Table 2. Excellent results were obtained. Accuracy of the system is better than the resolution of the micrometer.

Table 2. Comparison of Micrometer and Camera Readings at Room Temperature.

Micrometer* (inches)	Camera (inches)	Difference x 10^6 (inches)
0	0.000002	2
0.025	0.025003	3
0.050	0.050044	44
0.075	0.075040	44
0.100	0.100050	50
0.125	0.125047	47
0.150	0.150085	85
0.175	0.175029	29
0.200	0.200023	23

*Micrometer scale can be read to 0.0001 inches.

The following reduced size computer screens (Figures 8, 9, and 10) are typical for room temperature tests. L_o is the initial spacing of 0.5 inches plus one half the width of each of the gauge marks, i.e., 0.51562 inches is the center to center distance of a 0.5 inch space marked with 1/64-inch thick gauge marks. ΔL is calibrated as the displacement in inches.

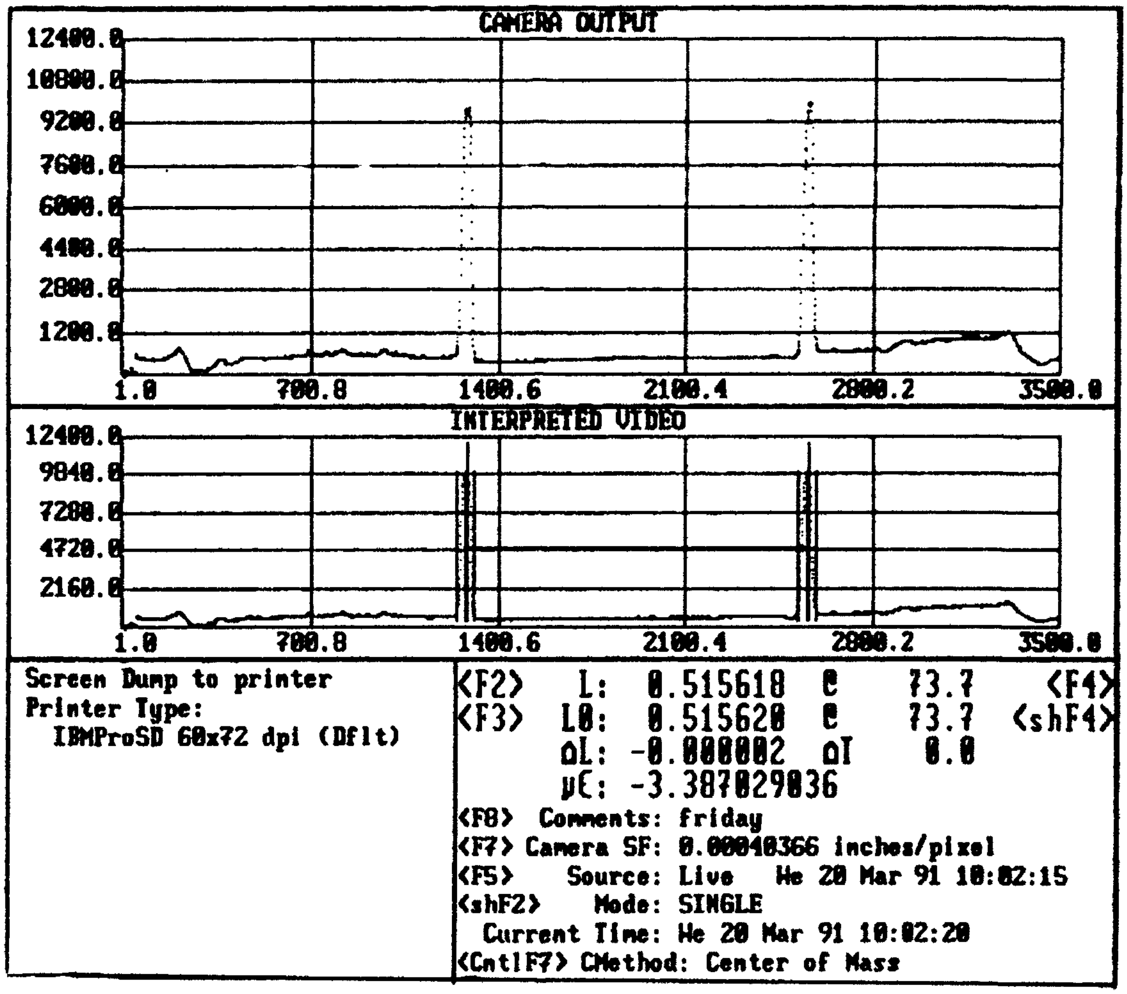

Figure 8. Shows a camera scan of the initial condition for the micrometer readings. The system was zeroed and then scanned. This particular scan measured zero to 0.000002 inches.

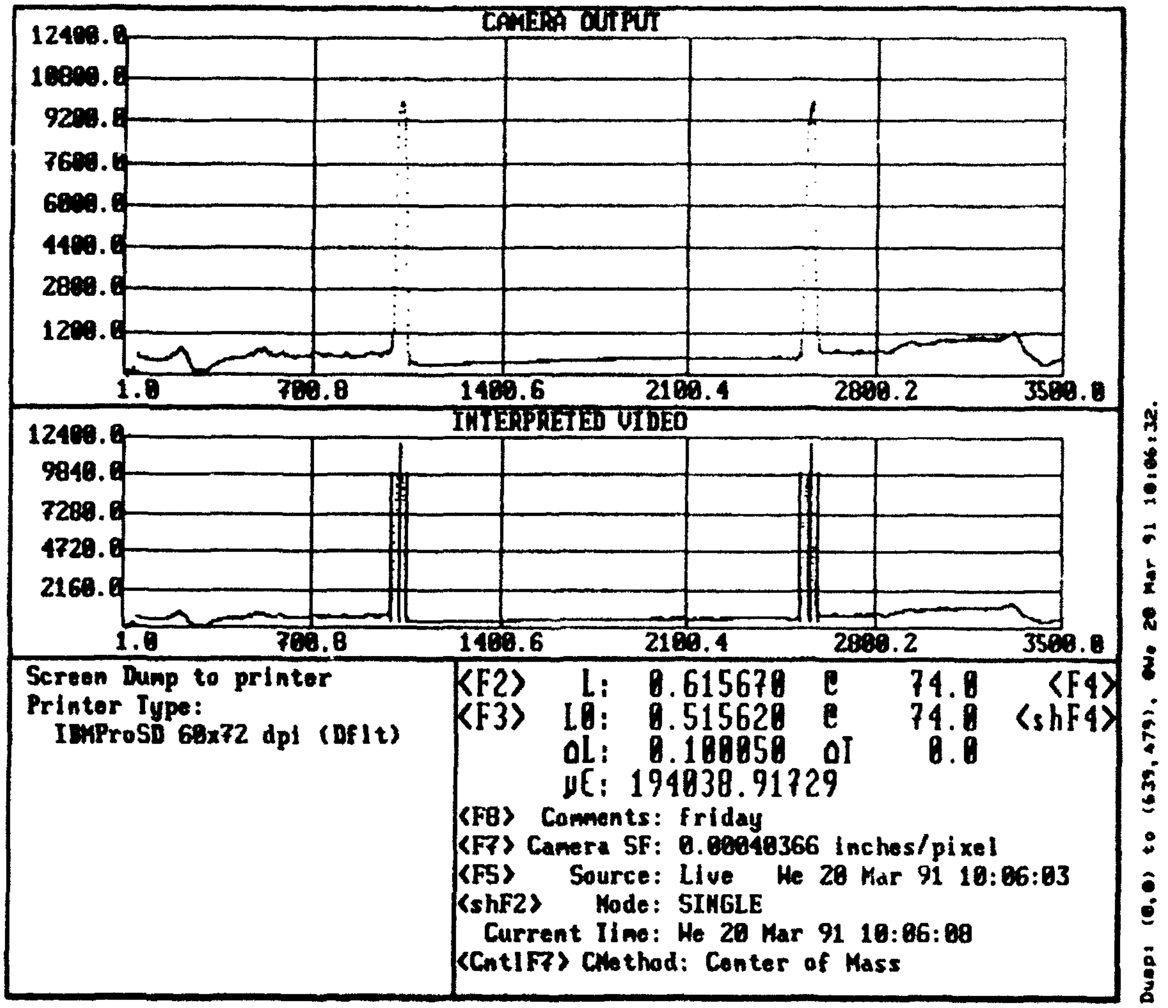

Figure 9. Shows a scan of the camera measuring a 0.1000 inch displacement within 50 microinches. Micrometer resolution 0.0001 inches.

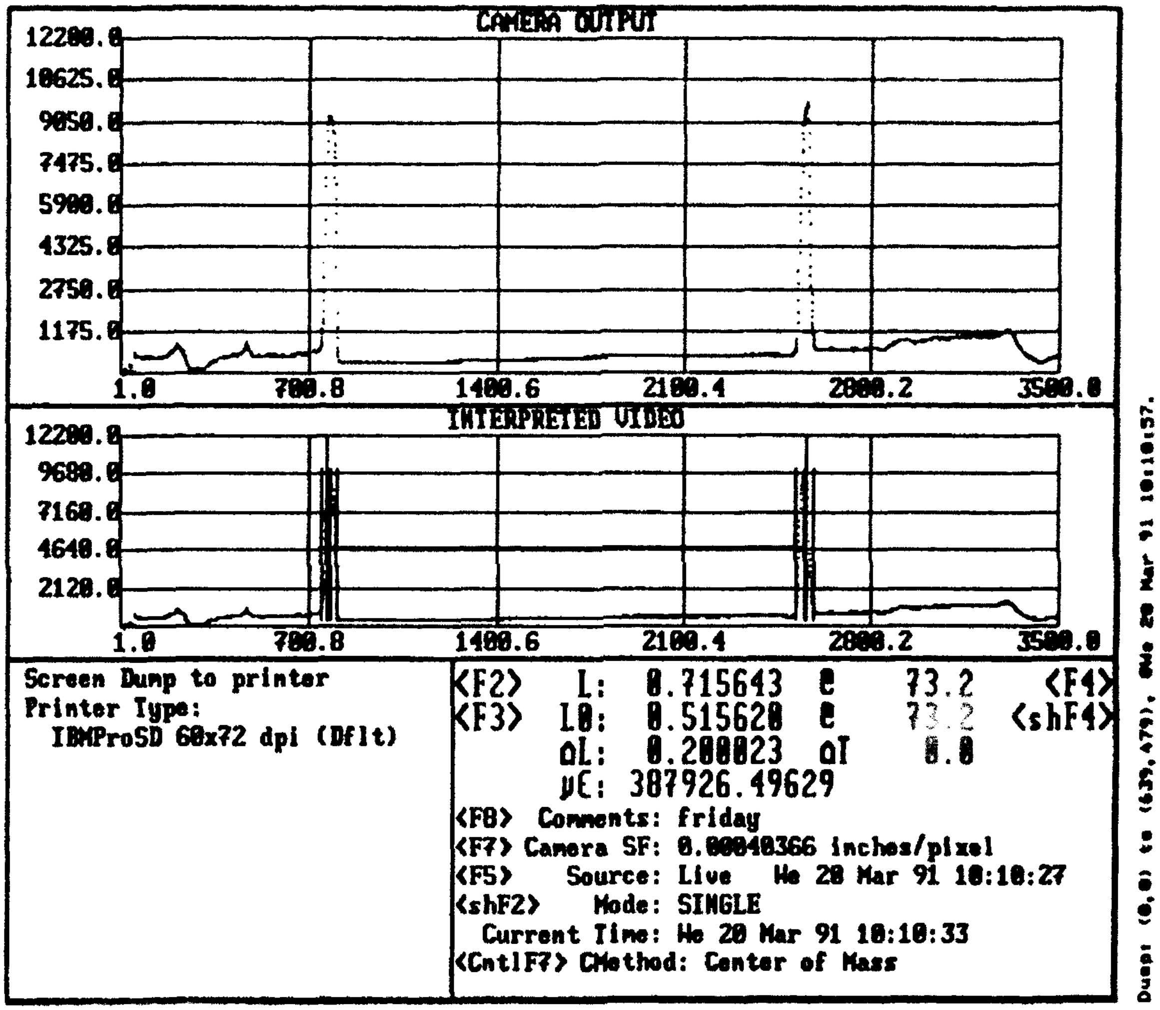

Figure 10. Shows the final measurement of the series, total displacement equal to 0.2000 inches. Micrometer resolution 0.0001 inches.

Elevated Temperatures-Nonuniform Unstable Conditions

The following camera scans were taken at the highest temperatures achieved in tests at Terra Tek. The heating is neither controlled nor stable enough to allow comparison of actual strain measurements. However, the scans demonstrate the camera's ability to identify and precisely locate gauge marks at extreme temperatures. The sample was a strip of stainless steel marked with high temperature ceramic cement. In order to achieve relatively uniform temperature in the gauge section, the gauge marks were placed close together. Figure 11 is a scan taken at 1848°F. A green, narrow band pass filter was used to mask the luminescence of the sample from the camera. The quality of the image is excellent with low background effects. Figure 12 was taken at 2167°F through the same filter. While the quality remains good, the effects of the sample luminance can be seen as the background level rises. (The characteristic wave length of the radiation from the sample is approaching the band-pass of the green filter.)

Other Results

During the course of this project, attempts were made to evaluate other types of reference marks. Some of these results may prove useful.

For example, instead of applied gauge marks a test sample was prepared with two small holes. The sample was illuminated from behind and the camera was aligned with the holes. Figure 13 shows a typical result. For samples that include holes (or that could be drilled without effecting the results) this method offers additional possibilities for illumination by laser or other specialized source. An alternative to this method was attempted using no illumination or filters on the camera. A sample with two holes was heated to provide self-luminance. The holes obviously did not glow and provided a contrasting dark output to the camera. The software allows the camera image to be inverted and dark gauge marks to be identified. Owing to

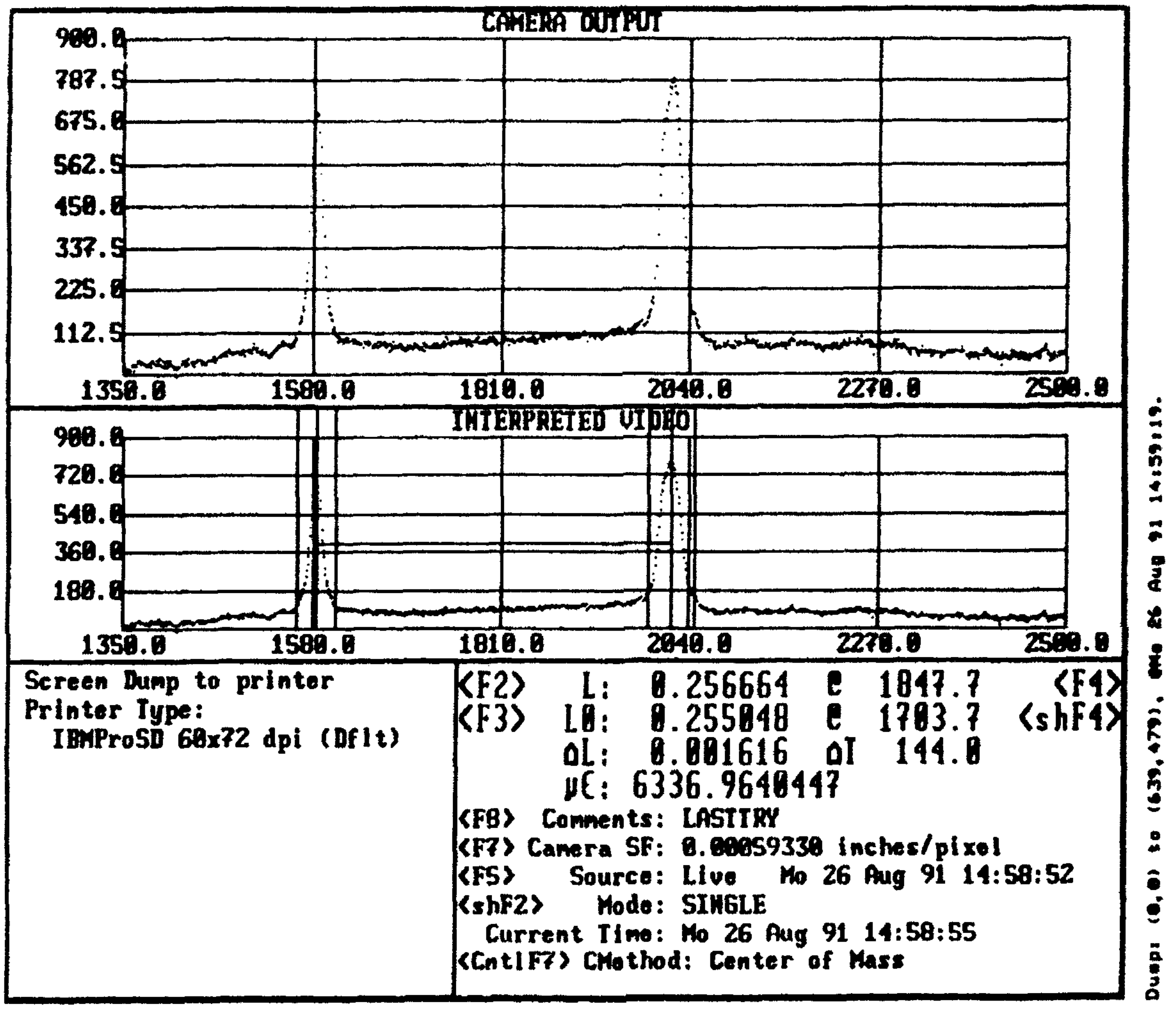

Figure 11. Shows a camera scan at 1848°F.

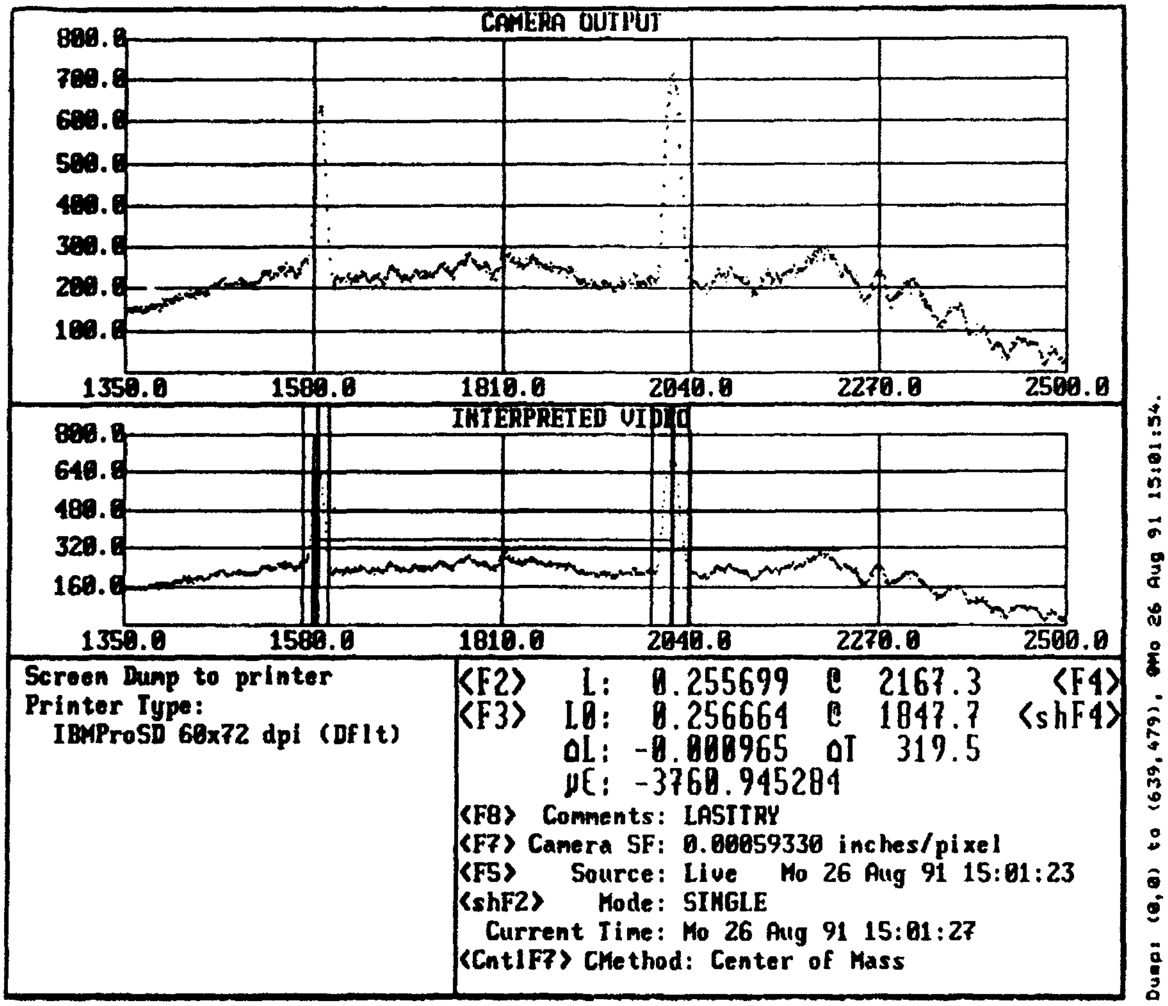

Figure 12. Shows a camera scan at 2167°F. Note the increasing level of background radiation.

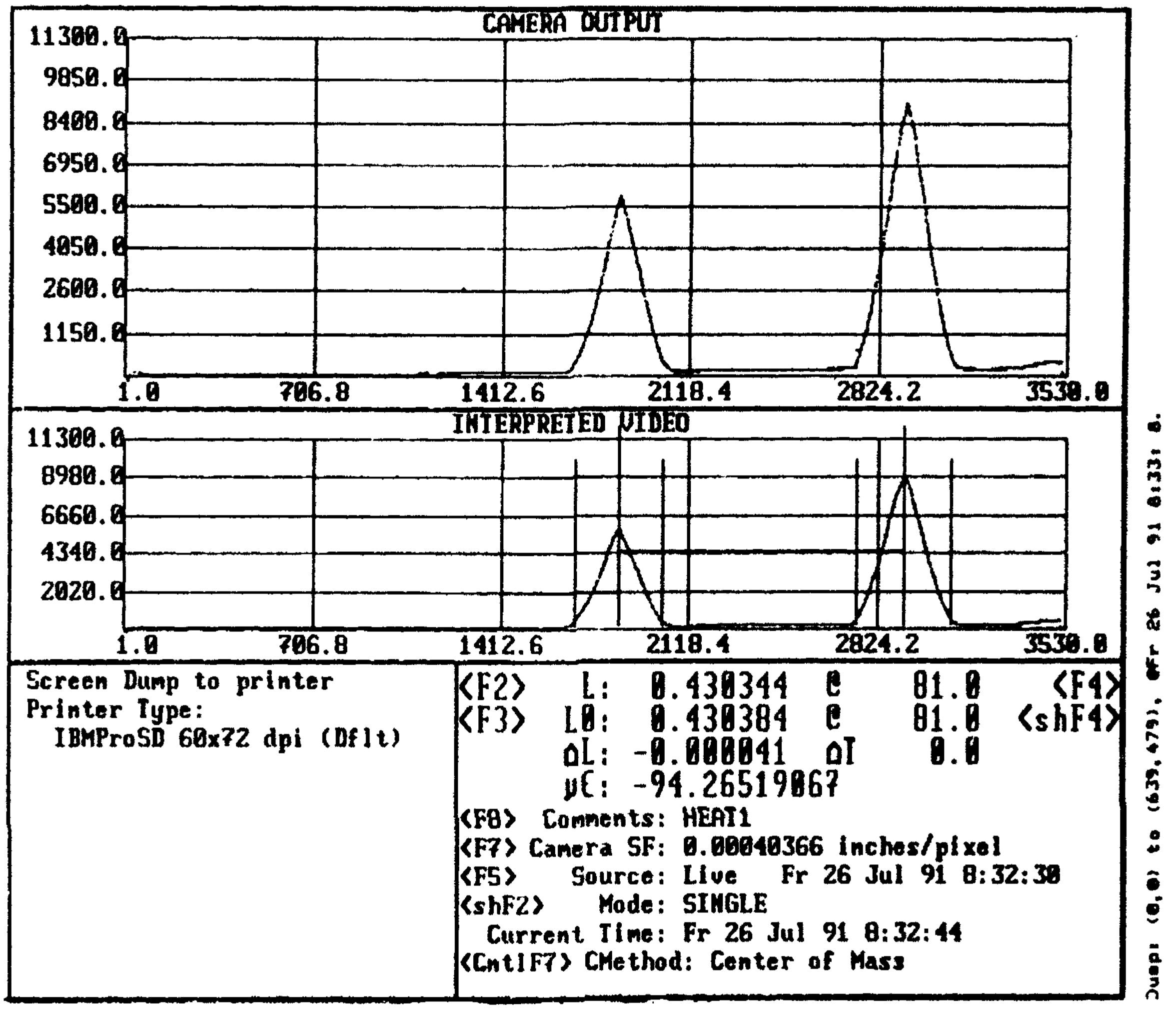

Figure 13. Shows a computer scan of a sample with two holes illuminated from behind.

limitations of our heating system, a full scan (two holes and the surrounding material) that demonstrated this method could not be obtained. It was clear, however, from the partial results obtained that the holes could be identified and that this technique may prove useful for very high temperatures and where the test sample contains holes.

IV. CONCLUSIONS

The optical, high-temperature, strain measurement system developed and evaluated for this project provides unique capabilities to measure strain and displacement in a wide variety of applications. The range of the system was demonstrated to 40%. The ability to make accurate measurements remotely and at high temperatures will extend the possibilities for characterizing new materials in difficult environments.

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