N93-13669

ABSTRACT

High-Temperature Strain Measurement Techniques: Current Developments and Challenges

Keynote Address by

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PRC, Inc., Edwards, CA

Since 1987, a very substantial amount of R&D has been conducted in an attempt to develop reliable strain sensors for the measurements of structural strains during ground testing and hypersonic flight, at temperatures up to at least 2000 deg F. Much of the effort has been focused on requirements of the NASP Program. This presentation is limited to the current sensor development work and characterization studies carried out within that program. It is basically an assessment as to where we are now and what remains to be done in the way of technical accomplishments to meet the technical challenges posed by the requirements and constraints established for the NASP Program.

The approach for meeting those requirements and constraints has been multi-disciplinary in nature. It was recognized early on that no one sensor could meet all these requirements and constraints, largely because of the large temperature range (cyrogenic to at least 2000 deg F) and many other factors, including the most challenging requirement that the sensor system be capable of obtaining valid "first cycle data".

Present candidate alloys for resistance-type strain gages include Fe-Cr- Al and Pd-Cr. Although they have superior properties regarding withstanding very high temperatures, they exhibit large apparent strains that must either be accounted for or cancelled out by various techniques, including the use of a dual-element, half-bridge dummy gage, or electrical compensation networks. A significant effort is being devoted to developing, refining, and evaluating the effectiveness of those techniques over a broad range in temperature and time.

In the quest to obtain first-cycle data, ways must be found to eliminate the need to prestabilize or precondition the strain gage, before it is attached to the test article. It should be noted that present NASP constraints do not permit prestabilization of the sensor, in situ. Gages are currently being "heat treated" during manufacture in both the wire- and foil-type resistance strain gages, and evaluation is in progress. In addition, the "gage-on-shim" concept is being revisited. That concept will permit heat treatment of the gage during manufacture, before attachment on the test article. Also, it may permit the individual calibration of each gage regarding gage factor and apparent strain.

Candidate alloys for the NASP include titanium metal-matrix and carbon-carbon composites. Although those materials have very attractive properties at elevated temperatures in terms of strength and weight, they pose significant attachment problems. Methods for making reliable strain gage and thermocouple attachments to them are currently under development. Experience to date indicates that Rokide attachment of the sensor directly to the protective coating is easier than to the base material itself. However, interpreting strain data from gages attached in this way may prove difficult because of possible cracks in the coating that form "islands" and the mobility of those "islands". It is concluded, therefore, that major technical challenges lie ahead as we proceed to meet the stringent strain sensor requirements and constraints of the NASP Program.

OUTLINE

I. INTRODUCTION

- CURRENT STATE-OF-THE-ART
  - RESISTIVE STRAIN GAGES
  - CAPACITIVE GAGES
  - CLIP GAGE
  - ELECTRO-OPTICAL METHODS
  - NEED FOR HIGH TEMPERATURE STRAIN MEASUREMENTS
  - NEED FOR RELIABLE ATTACHMENT TECHNIQUES
  - NEED TO REACH TECHNICAL CLOSURE ON CHOICE OF LEADWIRES
- NEED FOR MORE PHYSICAL AND MECHANICAL PROPERTIES DATA FOR NASP CANDIDATE MATERIALS, INCLUDING β21S TMC
- CRITICALITY OF GAGE LOCATIONS AND ORIENTATIONS, AND HOW DO WE DETERMINE WHERE TO PUT THEM BEFORE GAGING THE TEST ARTICLE?

II. A MAJOR NASP REQUIREMENT AND CHALLENGE

- GET VALID FIRST CYCLE DATA TO AT LEAST 1500°F
- HOW BIG A TECHNICAL CHALLENGE IS IT?

III. GAME-PLAN FOR DEALING WITH THIS TECHNICAL CHALLENGE

- CONSIDER USE OF AN EXISTING GAGE IN THE UNTREATED CONDITION THAT HAS ACCEPTABLE PERFORMANCE TO 1500°F
- SUPPRESS THE APPARENT STRAIN
  - USE A REMOTE DUMMY GAGE COMPENSATION SYSTEM
  - USE TEMPERATURE-COMPENSATED GAGES
  - USE GAGES THAT CAN BE HEAT-TREATED DURING MANUFACTURE

USE WELDABLE GAGES (EATON, ETC.) OR SHIM-MOUNTED BCL OR NZ-2104 GAGES THAT CAN BE PRESTABILIZED, PRECONDITIONED, OR PRECALIBRATED PRIOR TO INSTALLATION ON THE TEST ARTICLE OR SPECIMEN

IV. CURRENT ACTIVITIES AT DRYDEN

A. DEVELOPMENT OF REMOTE DUMMY GAGE TEMPERATURE-COMPENSATION SYSTEMS

B. DEVELOPMENT OF A DUAL-ELEMENT TEMPERATURE-COMPENSATED GAGE

C. DEVELOPMENT OF SHIM-MOUNTED GAGES THAT CAN BE PRESTABILIZED, PRECONDITIONED OR CALIBRATED PRIOR TO ATTACHMENT ON TEST ARTICLE OR SPECIMEN

D. DEVELOPMENT OF AN OPTIMUM WELD SCHEDULE FOR ATTACHING WELDABLE GAGES WITH INCONEL FLANGES (EATON GAGE, ETC.), OR GAGES MOUNTED ON INCONEL SHIMS, TO β21S TMC

E. DEVELOPMENT OF OPTIMUM PRESTABILIZATION SCHEDULE FOR BCL GAGES

F. DEVELOPMENT OF ELECTRO-OPTICAL STRAIN MEASUREMENT SYSTEM (GRANT-CONTRACT TO IIT) FOR STRUCTURAL TESTING TO 2500°F, OR BEYOND

G. PERTINENT GAGE CHARACTERIZATION STUDIES, INCLUDING A STUDY TO DETERMINE CHARACTERISTICS OF UNTREATED BCL GAGES TO AT LEAST 1500°F

H. COMPONENT TESTING AND GAGING

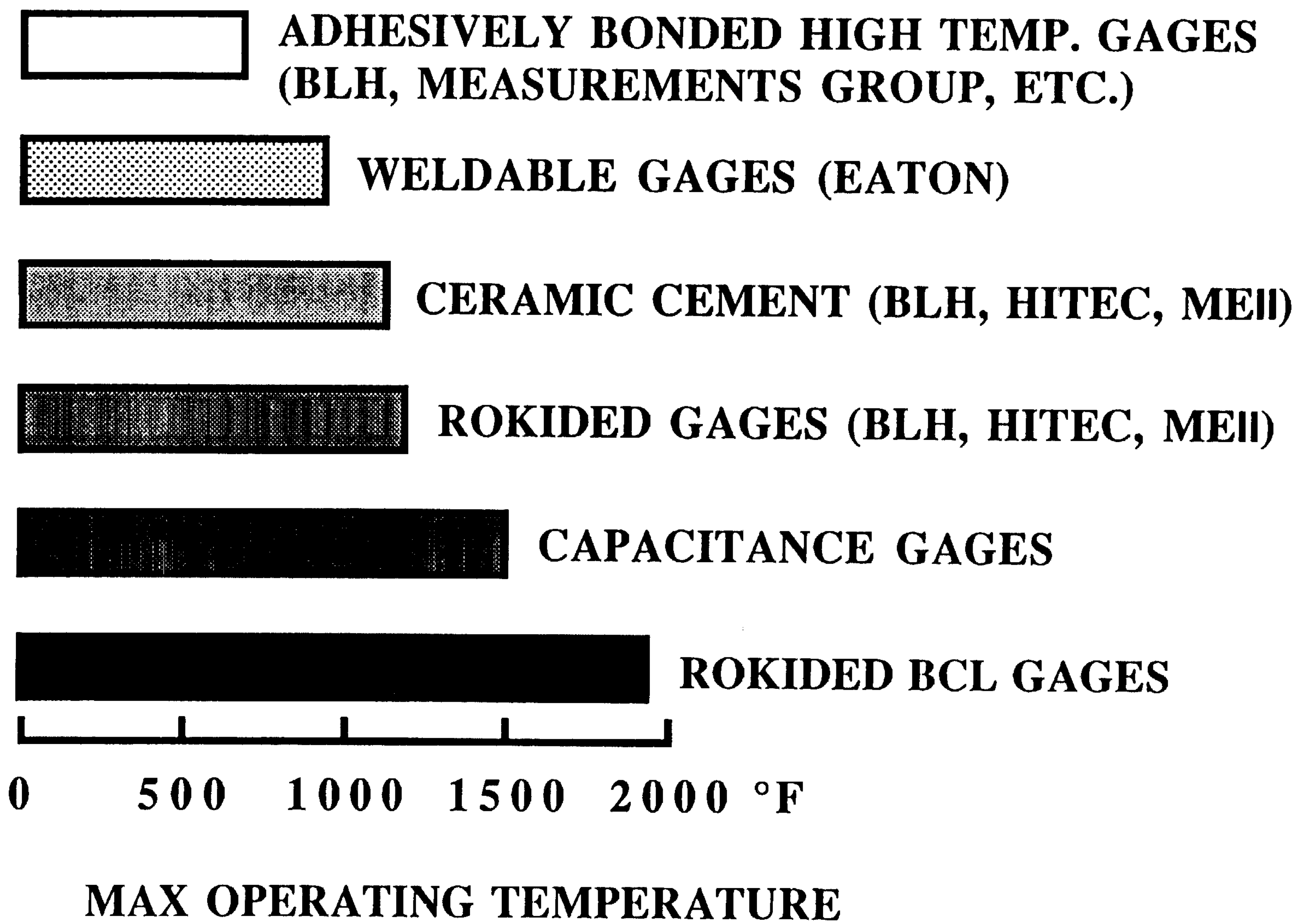
V. ON-GOING WORK AT LeRC

- Pd-13Cr TEMPERATURE-COMPENSATED GAGE
- GWP 29

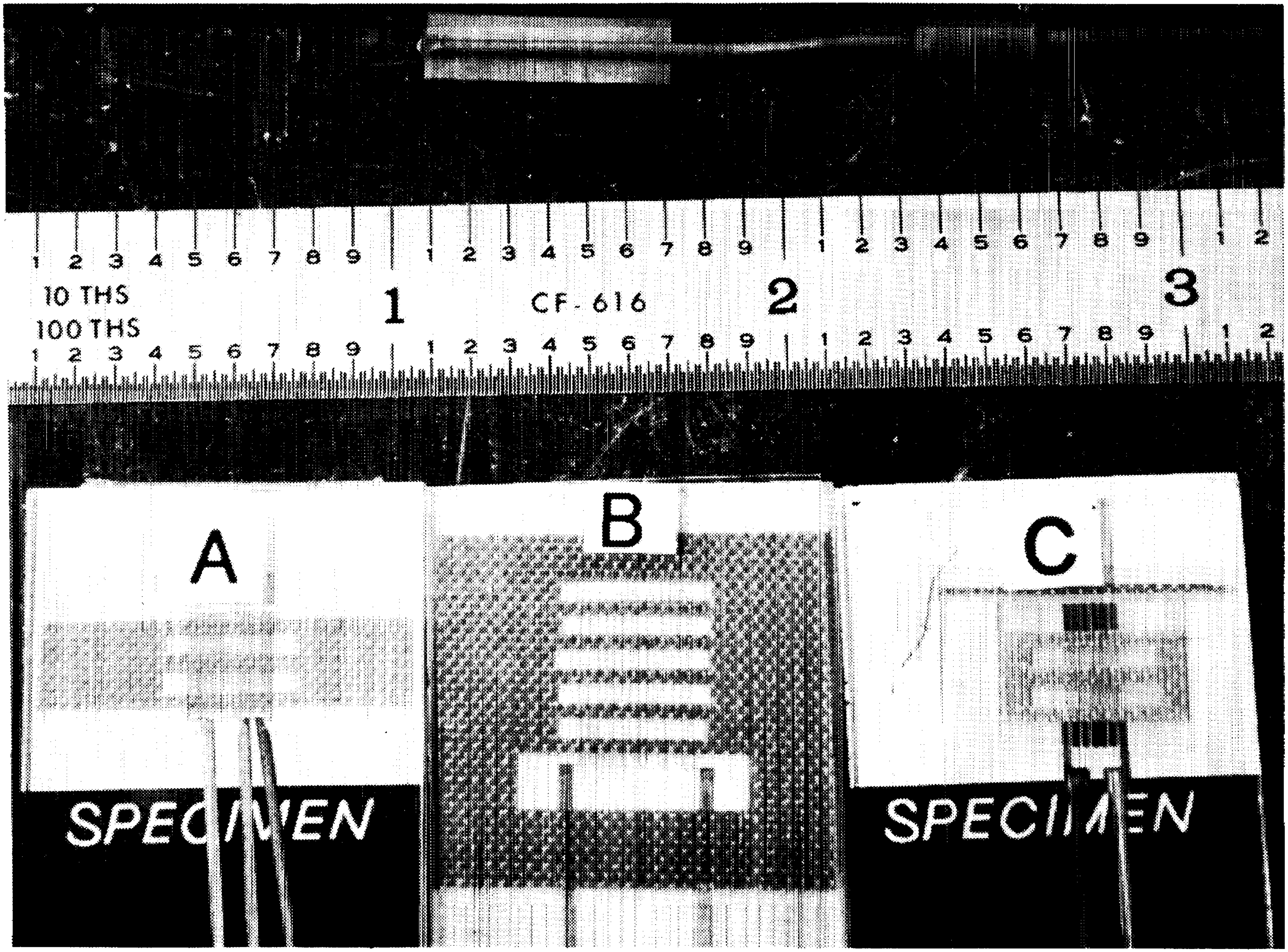
VI. ON-GOING WORK AT LaRC

- TEMPERATURE-COMPENSATED GAGES
- GAGE ATTACHMENT TECHNIQUES
- GAGE CHARACTERIZATION STUDIES

VII. CONCLUDING REMARKS



STATE OF THE ART OF EXISTING ELECTRIC RESISTANCE AND CAPACITANCE STRAIN GAGES



A: Untreated, Temperature-compensated BCL gage; B: Standard, Untreated BCL gage; C: NZ-2104 gage. At top: Eaton SG425 gage with Inconel 600 flange

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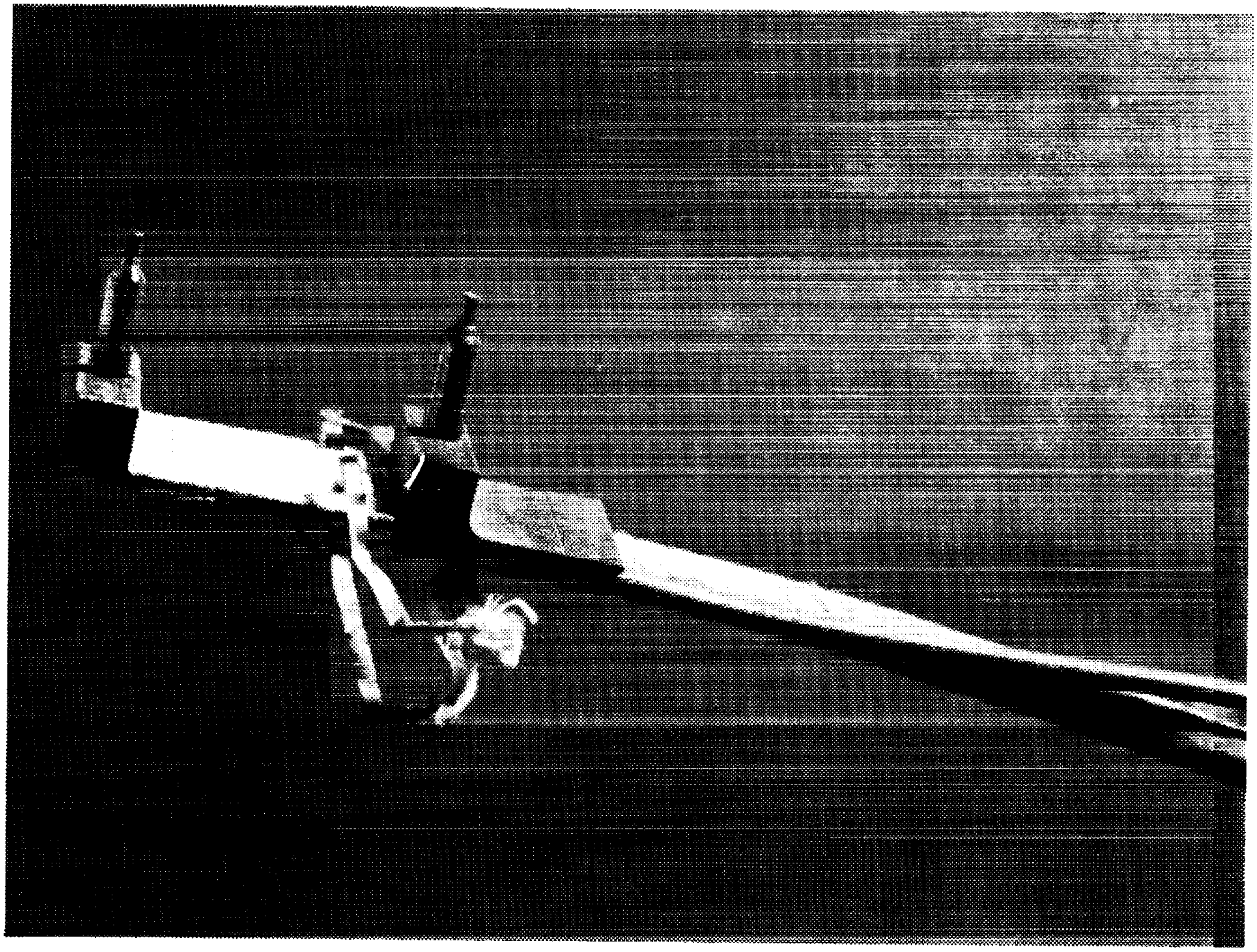
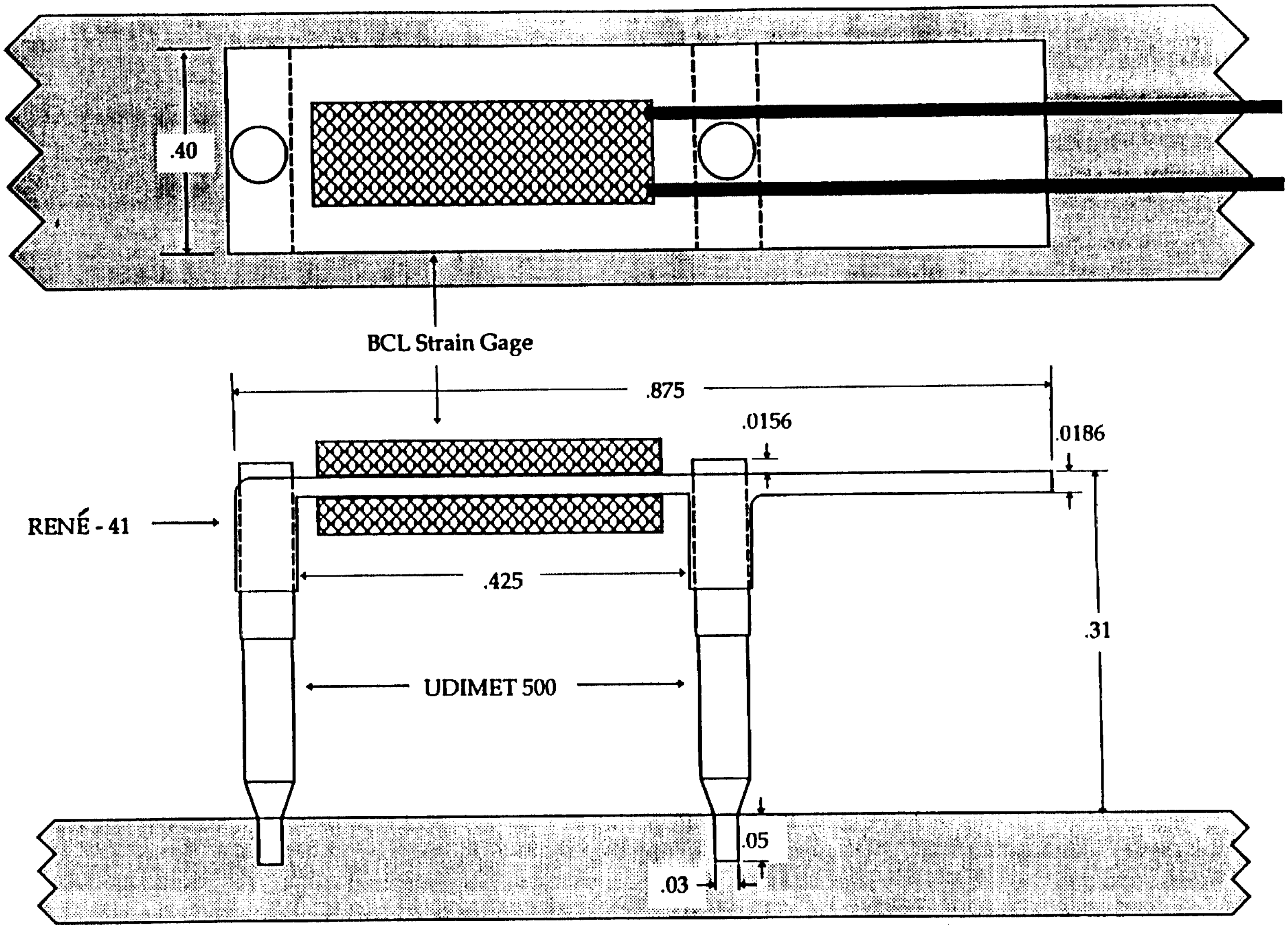
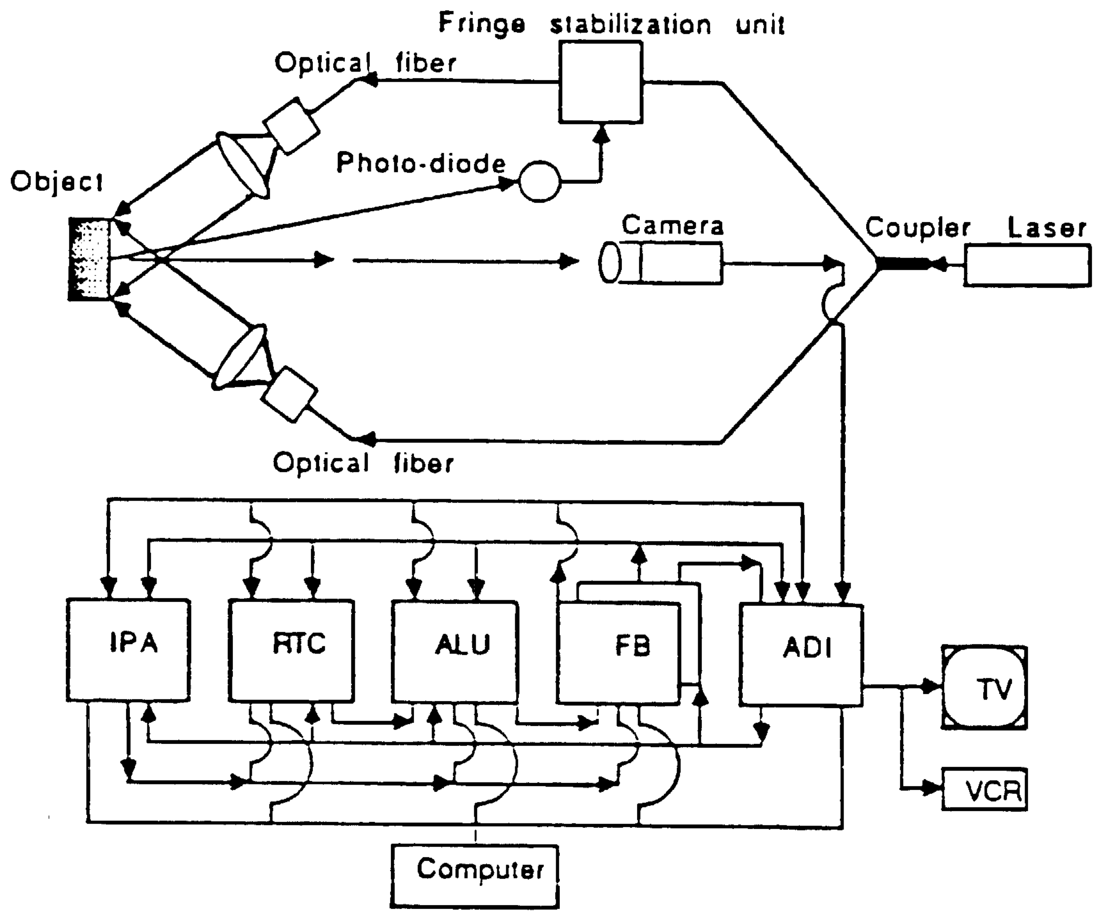


High-Temperature Clip Gage



BCL Clip Gage

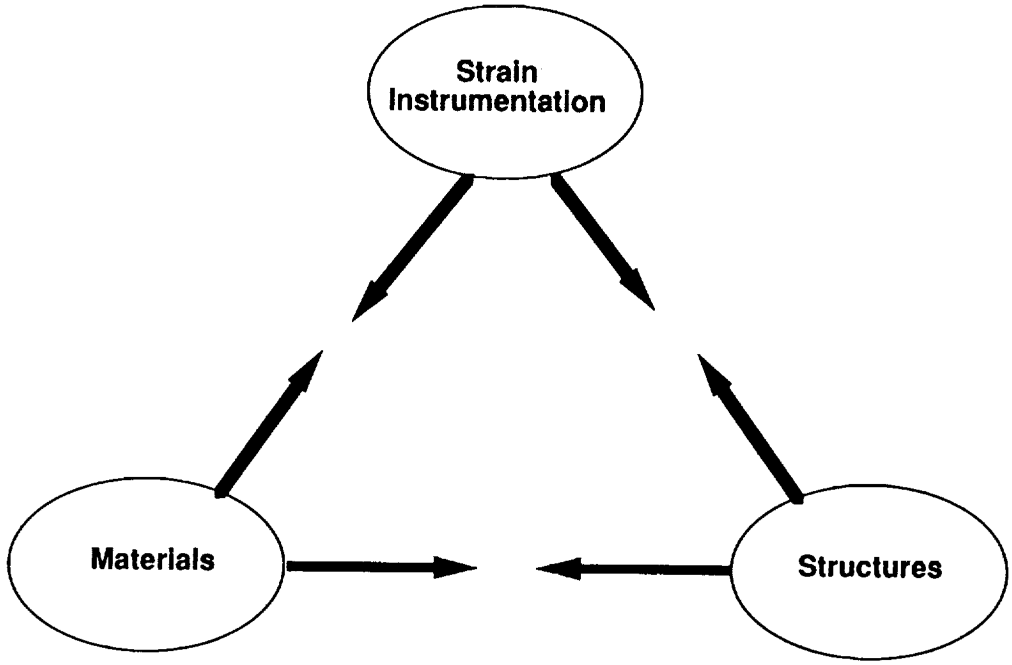


ADI - Analog to digital interface FB - Frame buffer ALU - Arithmetic and logic unit
RTC - Real time convolver IPA - Image processor accelerator

Schematic representation of the electro-optical system to measure strains

- # Needs for High Temperature Strain Measurements

  - NASP Structural Ground Tests
  - NASP Flight Tests
  - Validation of finite element computer codes for NASP stress analysis
  - Materials behavior studies, including determination of strains resulting from release of residual or fabrication stresses, during and after heating

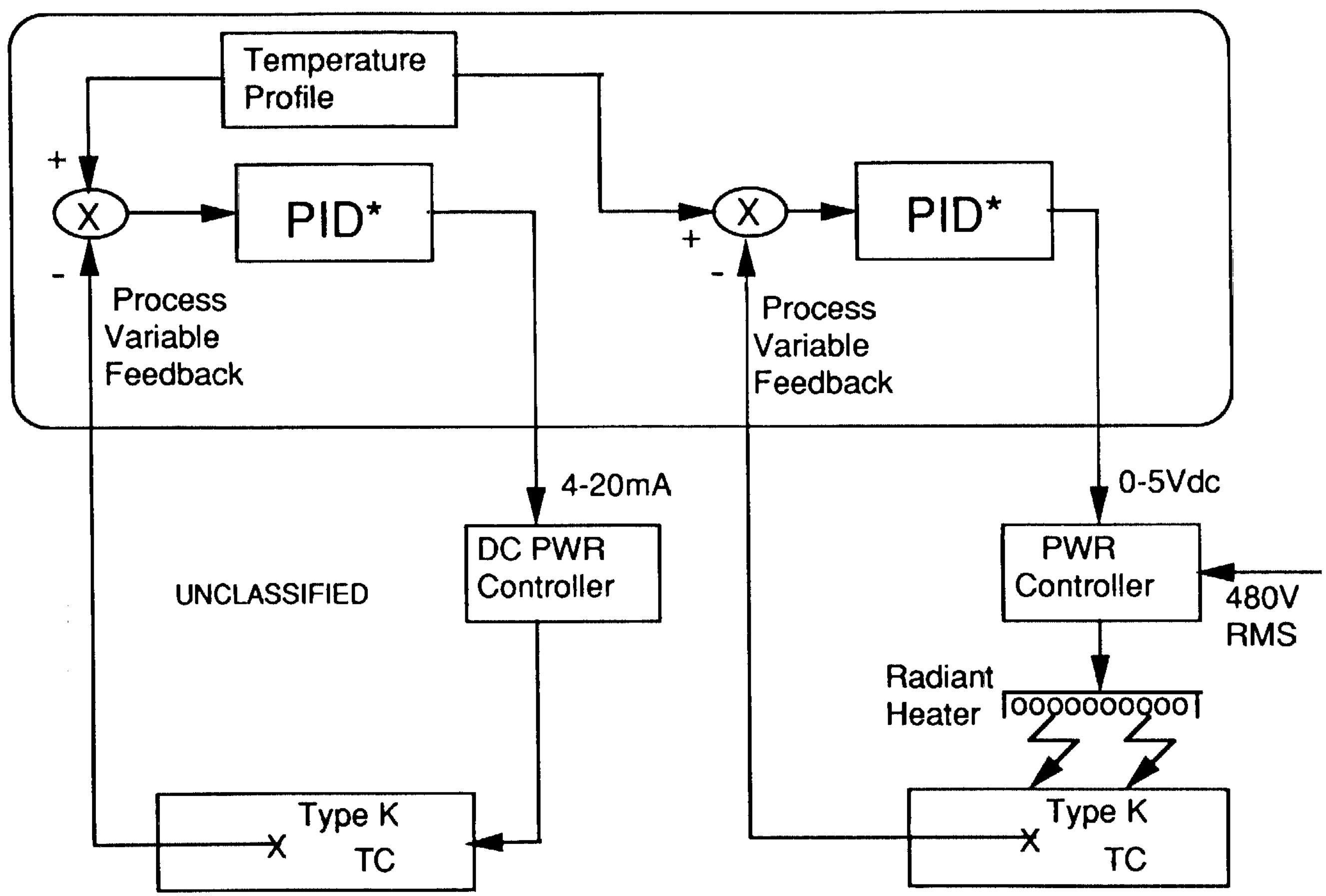


Effective Interfacing

- **Standard Prestabilization-Preconditioning Procedure**

  - Prestabilize the attached gages for 4 hours (minimum), at a temperature about 25°F above the maximum test temperature, in an air environment

  - After prestabilization, precondition the installed gages by subjecting them to 3 thermal cycles from room temperature to maximum temperature, and 3 mechanical cycles at maximum test temperature to a minimum of $\pm$ 2000 $\mu\varepsilon$

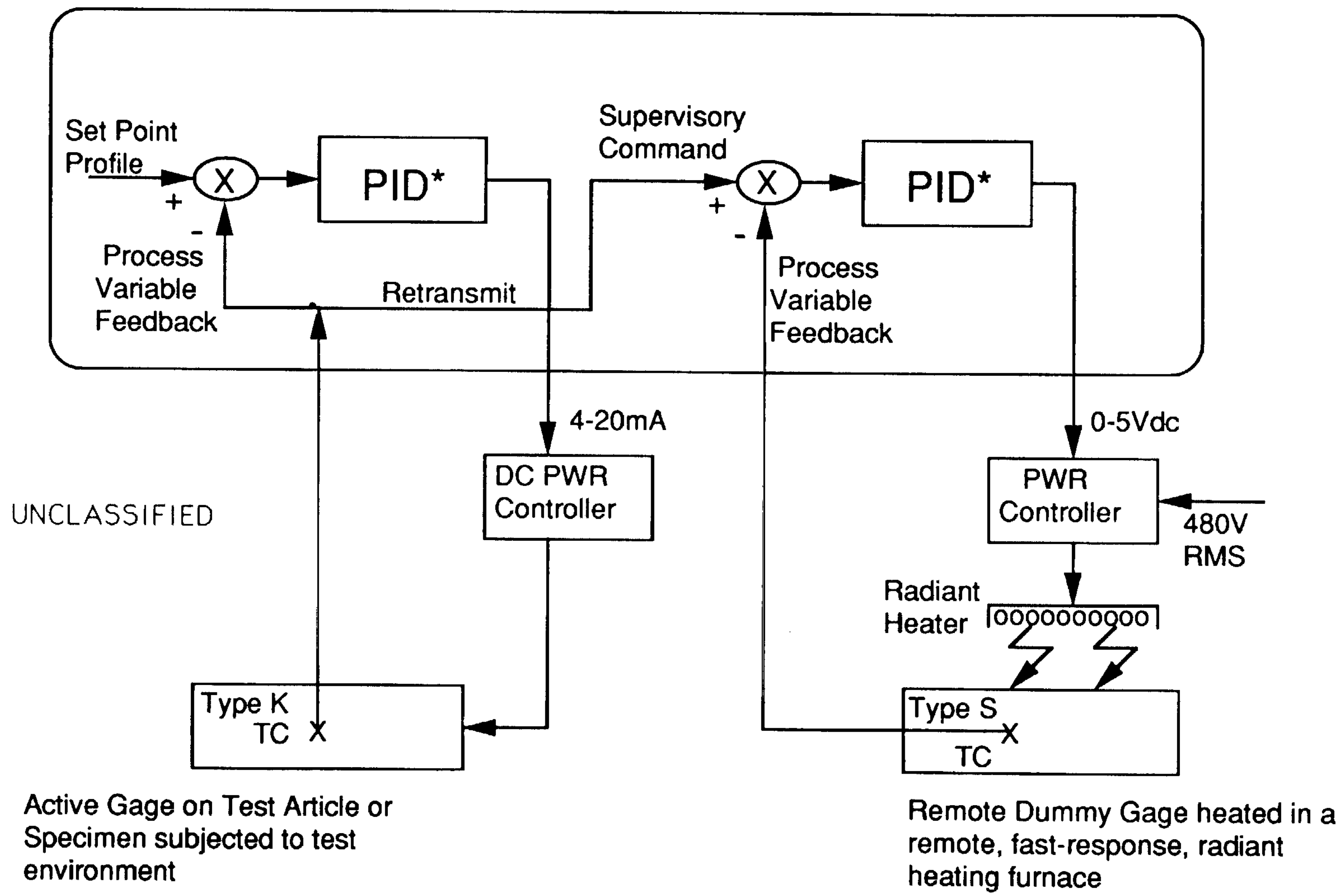


Active Gage on Test Article or Specimen subjected to test environment

Remote Dummy Gage heated in a remote, fast-response, radiant heating furnace

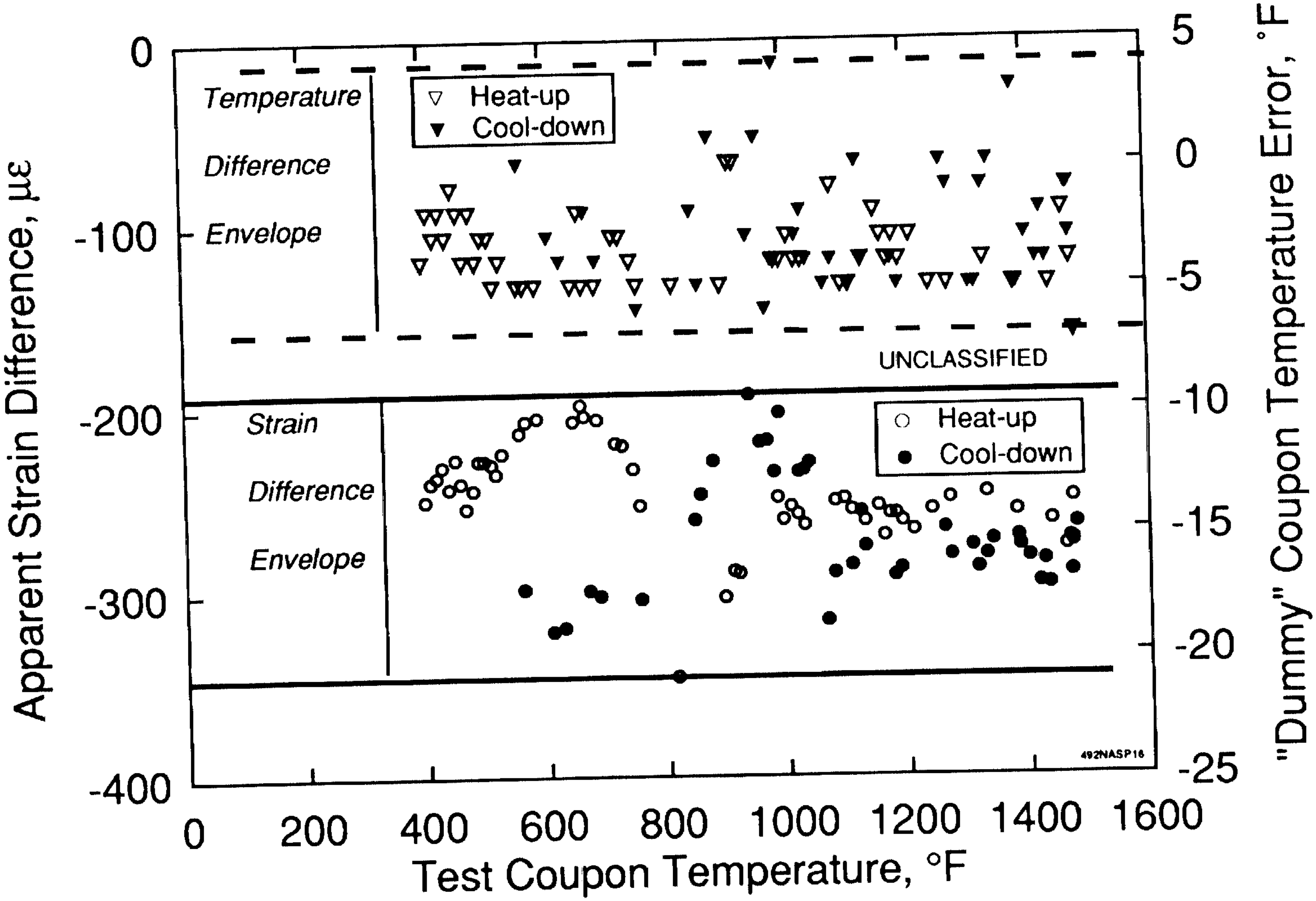
* - PID: Proportional-Integral-Derivative temperature controllers

Schematic of Breadboard Electronic Follower/Control System for Remote Suppression of Apparent Strain

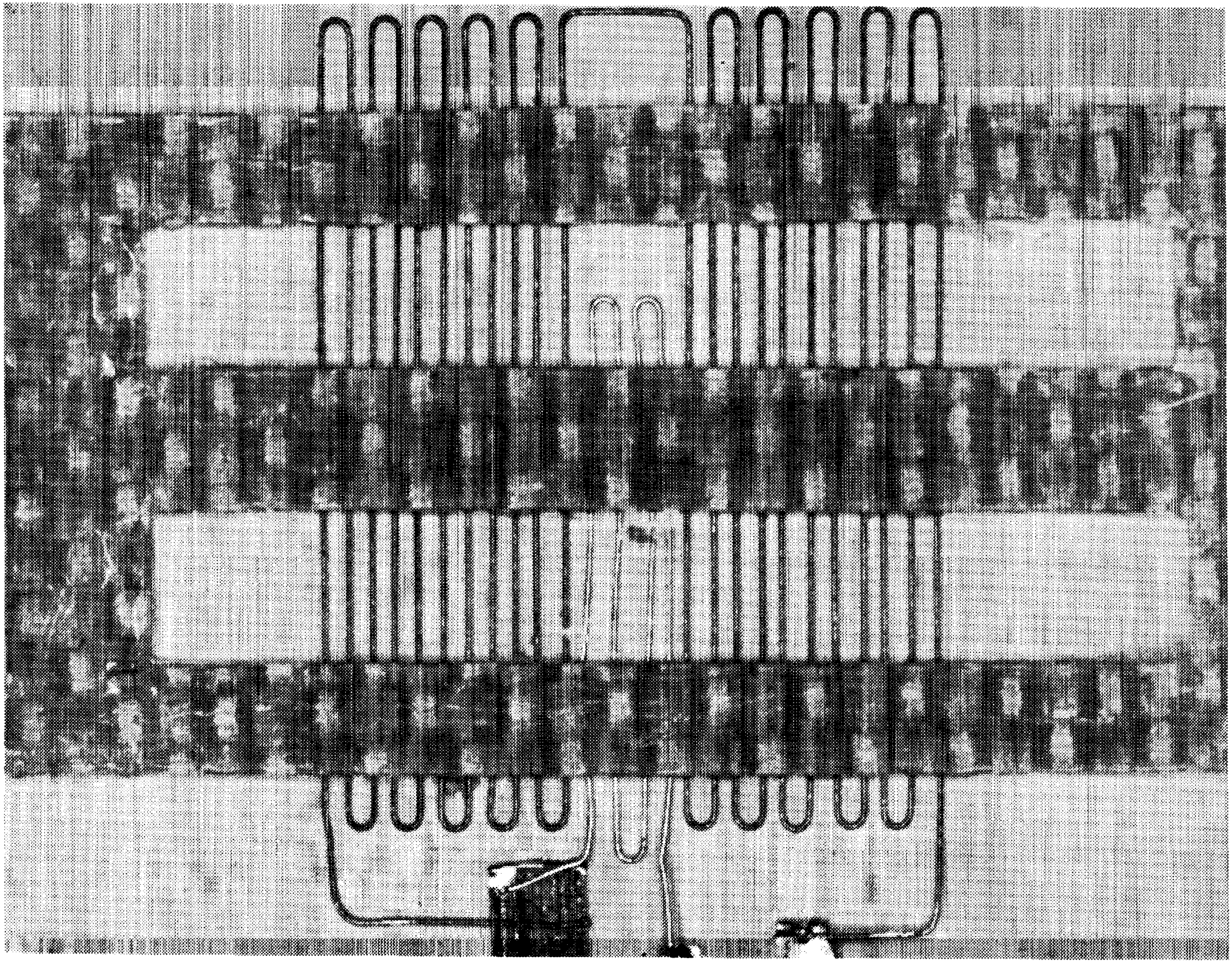


* - PID: Proportional-Integral-Derivative temperature controllers

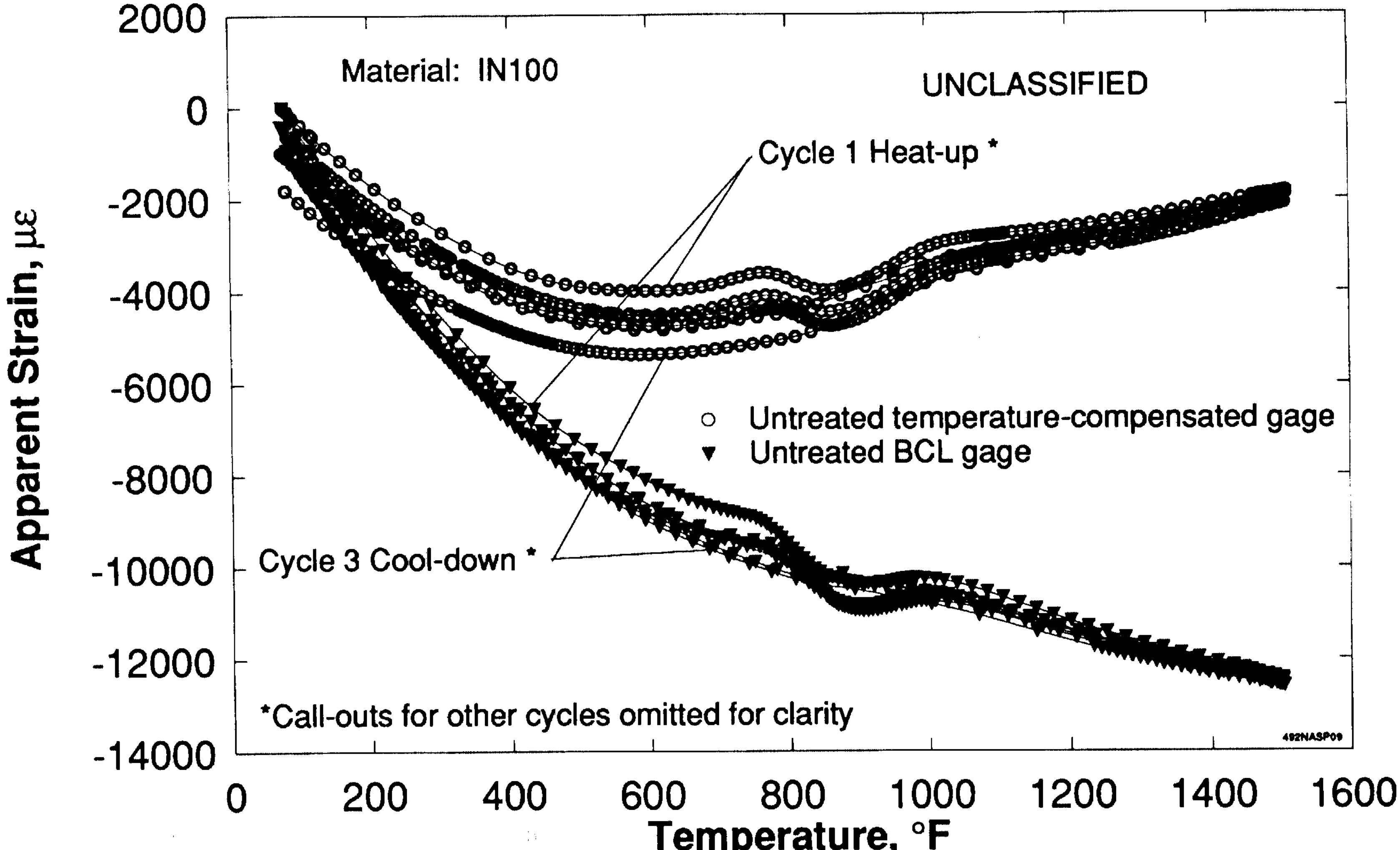
Schematic of Electronic Follower/Control System for Remote Suppression of Apparent Strain



Apparent Strain from an Untreated BCL Active Gage with Remote Dummy Gage. First Cycle Data.



BCL Dual-element Temperature-compensated Gage with central platinum compensating element



Apparent Strain of BCL Temperature-Compensated and Standard BCL Untreated gages

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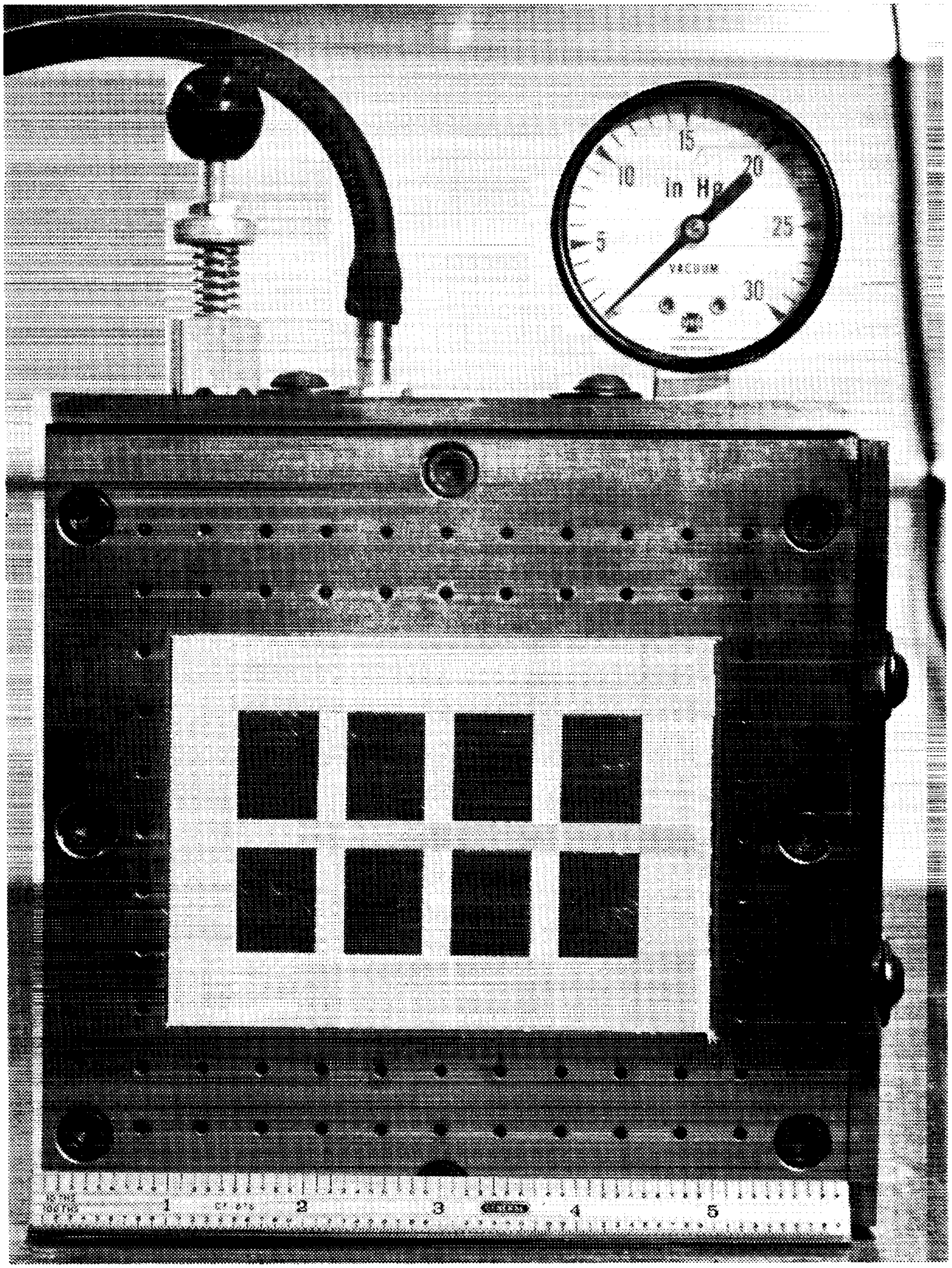
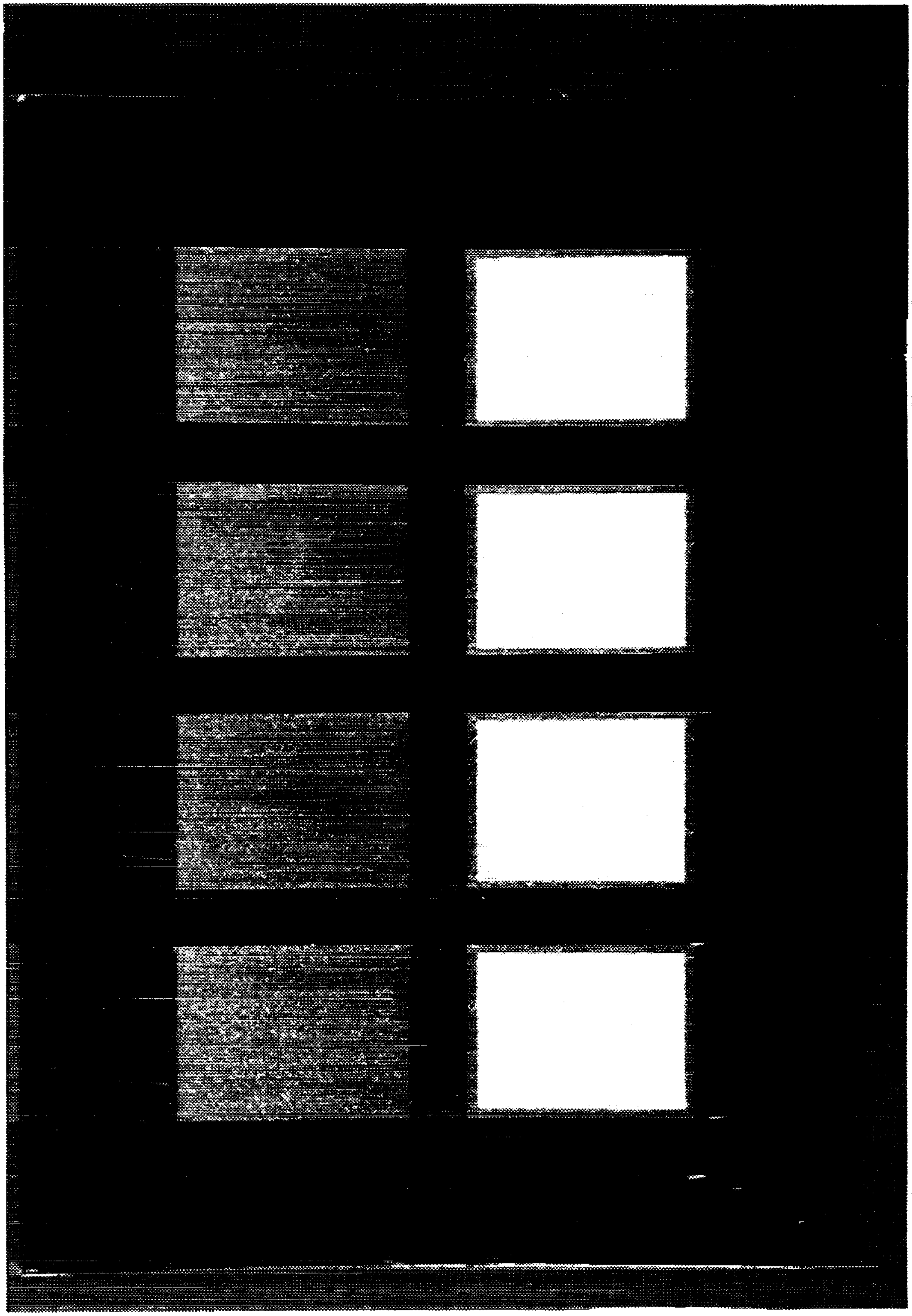
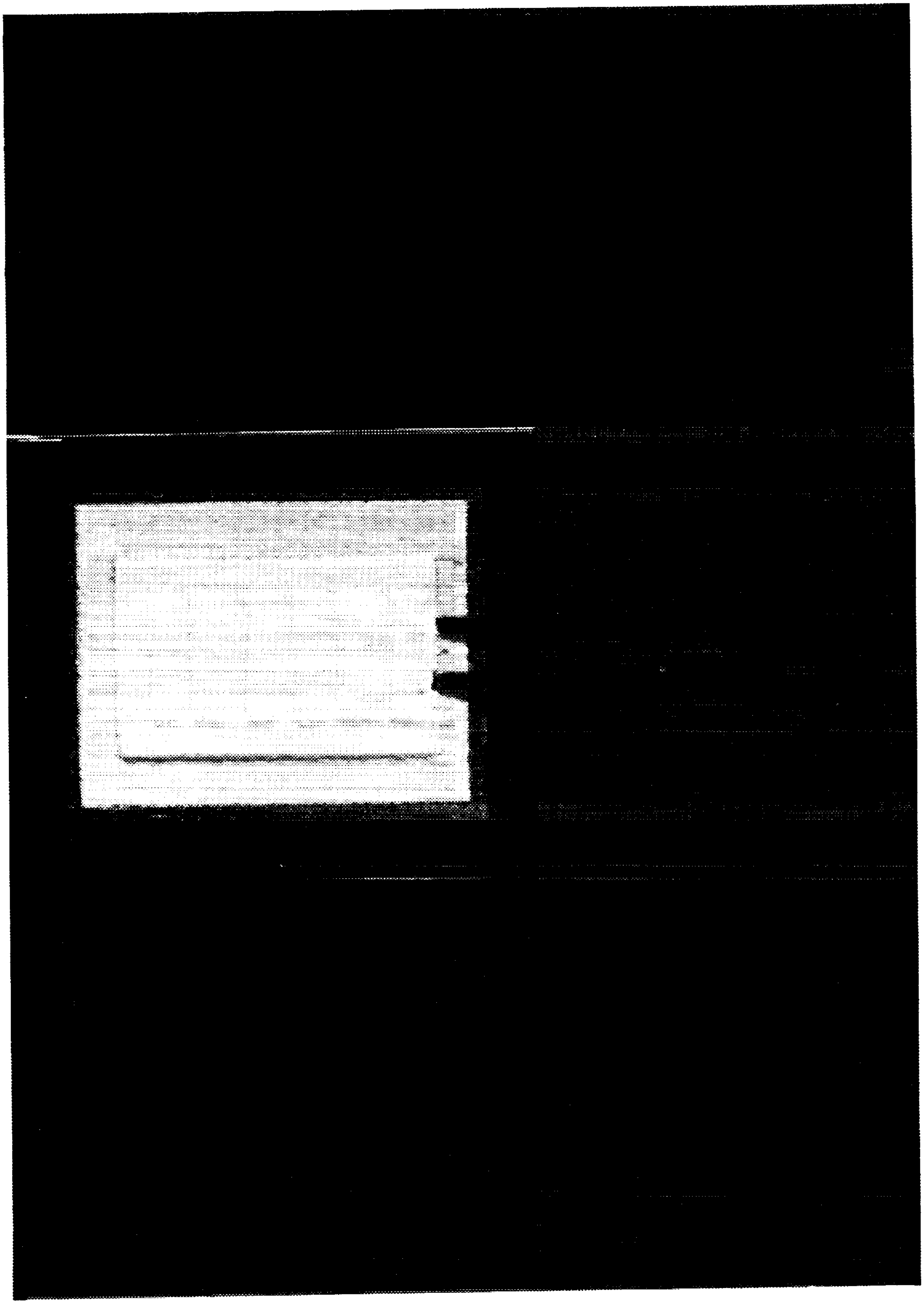


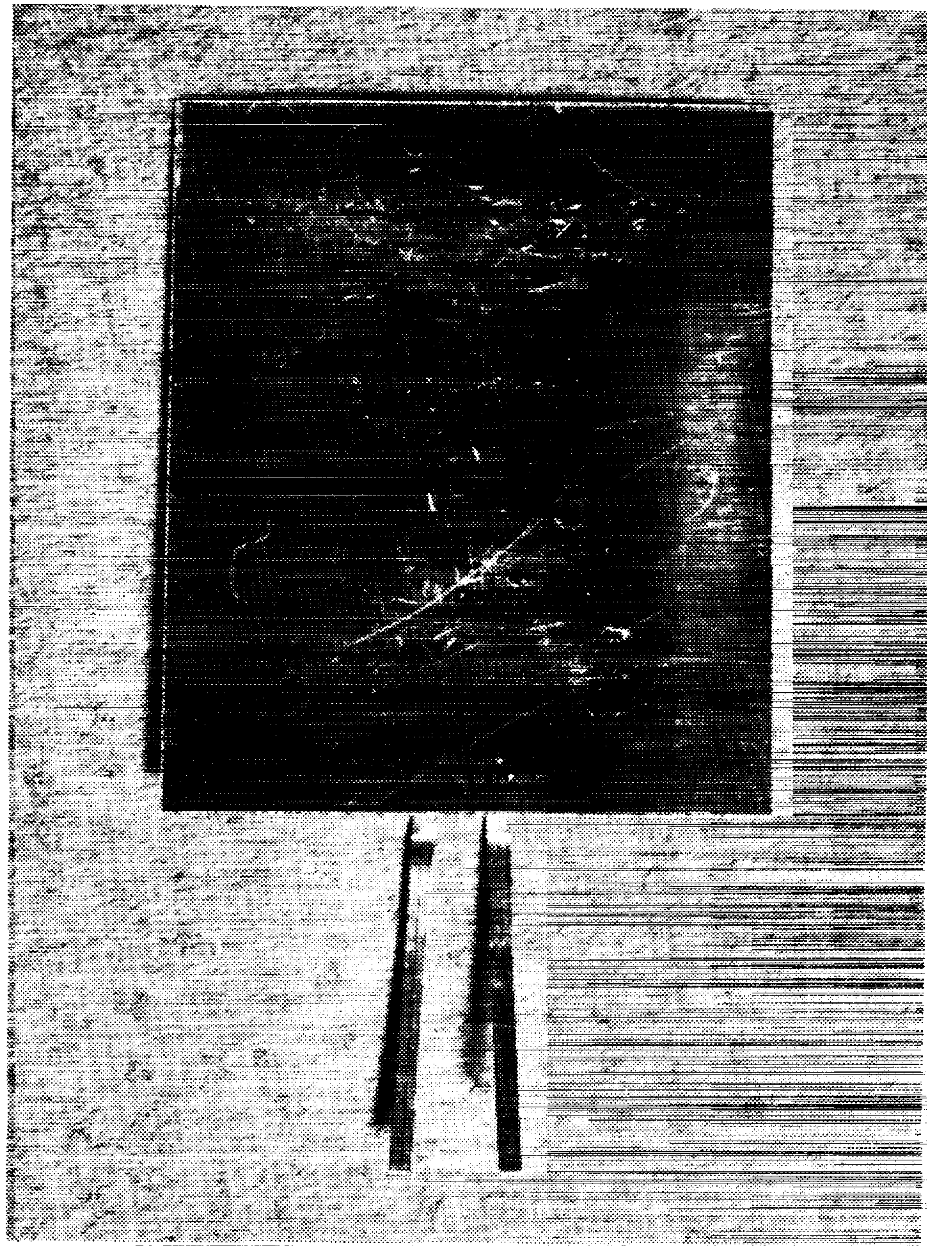
Vacuum Chuck used to hold Coupon flat during spraying



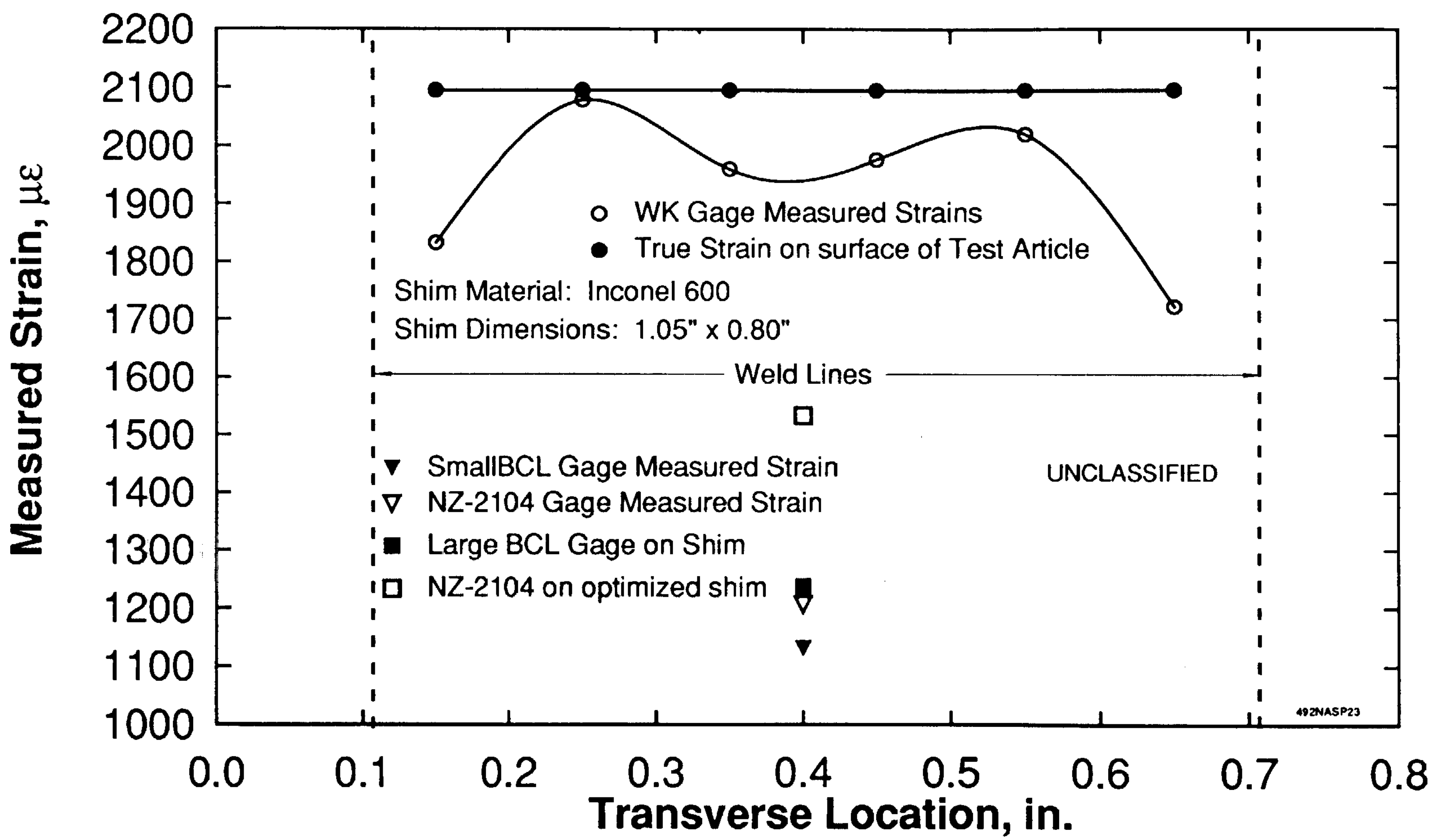
TOP: Plasma-sprayed Precoat of Metco 461 on Inconel 600, 5 mil Shim
BOTTOM: Rokide Insulating Substrate bonded to Precoat



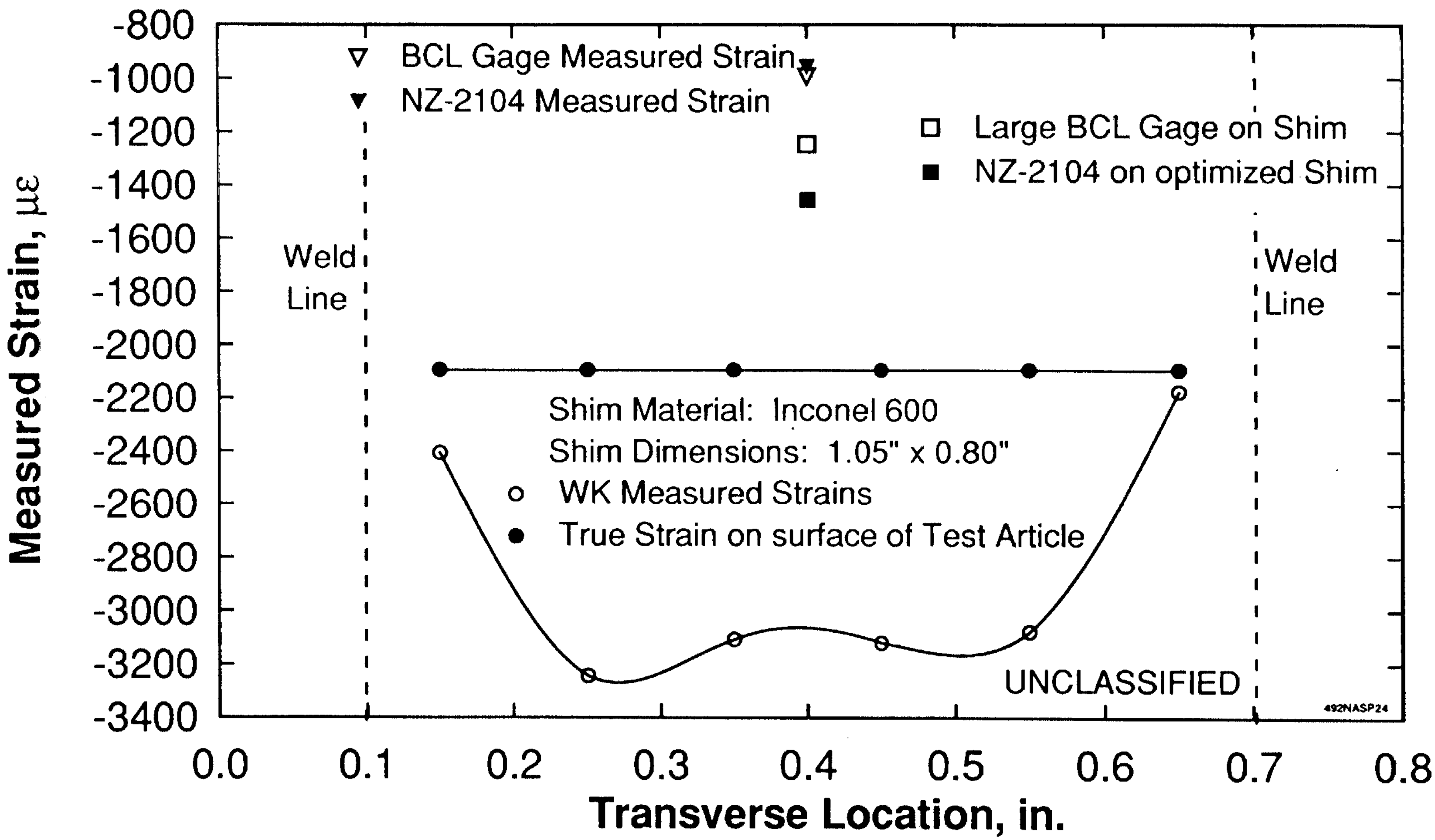
Complete NZ-2104 Gage Installation on Inconel 600 Shim



Back Face of Shim, after Gage Installation



Tensile Strain Distribution Across Transverse Section at Centerline of 5 mil Thick Shim



Compressive Strain Distribution Across Transverse Section at Centerline of 5 mil thick Shim

BCL-instrumented Shim Fatigue Data

Cycle No.	Maximum Measured Tensile Bending Strain	Maximum Measured Compressive Bending Strain
	με	με
1	1288	-1013
10	1304	-996
20	1304	-972
30	1304	-982
40	1302	-978
50	1302	-972
60	1299	-972
70	1302	-969
80	1300	-967
90	1299	-966
100	1299	-962

All data is at room temperature.
True Strain on calibration specimen was ±2095 microstrain.

Effective Gage Factors of Shimmed Gages

	Small BCL on Large Shim	Standard BCL on Large Shim	NZ-2104 on Large Shim	NZ-2104 on Optimized Shim
Tension	1.41	1.86	1.53	2.30
Compression	1.30	1.87	1.33	2.18

Nominal BCL Gage Factor is 2.36, nominal NZ-2104 Gage Factor is 2.60.
Shaded columns indicate latest test data.

Force		Watt-sec 10	15	20	25	30	35	40	45	50
F	6	Y3 N	**Y1** N	Y3 N	Y3 Y3	N Y3	N **Y1**	N Y3	N Y3	N N
o l	8	N N	Y3 N	Y3 Y3	**Y1** Y3	Y3 Y3	N **Y1**	N Y3	N Y3	N Y3
r b	10	Y3 N	Y3 N	**Y2** N	**Y1** Y3	**Y2** Y3	Y3 **Y2**	Y3 **Y1**	N Y3	N Y3
c s	12	N N	Y3 N	Y3 N	Y3 Y3	**Y1** Y3	Y3 Y3	Y3 **Y1**	Y3 Y3	N Y3
e	14	N N	N N	Y3 N	Y3 N	**Y1** N	Y3 Y3	Y3 **Y1**	N Y3	N Y3

Left-Hand side of box in matrix: Inconel 600, 2.8 mils/ Uncoated ß21S TMC
Right-Hand side of box in matrix: Inconel 600, 5.1 mils/ Uncoated ß21S TMC

All flanges 1.125" x 0.188"
Welder: Measurements Group Model P-28
Electrode: RWMA 2; Tip: .027"

Y1 : Very Good weld - Excellent nugget remained after peel test
Y2 : Good weld - Satisfactory nugget remained after peel test
Y3 : Good weld - Materials welded, but nugget was unsatisfactory
N : Not a good weld - Materials did not weld

Preliminary Inconel 600/ß21S Weld–Schedule Data

IN600 / ß21S Weld Joint Peel Test Results

		Flange Material		
		IN600 (2.8)	IN600 (5.1)	ß21S (2.5)
Weld Energy	W-s	*25*	*40*	*15*
Electrode Force	lbs	*10*	*10*	*10*
Average Peeling Force	lbs	5.30	7.74	4.62

IN600 / ß21S Weld-Joint Lap-Shear Test Results

		Flange Material (Thickness, mils)		
		IN600 (2.8)	IN600 (5.1)	ß21S (2.5)
Weld Energy	W-s	*25*	*40*	*15*
Electrode Force	lb	*10*	*10*	*10*
Average Breaking Stress	ksi	103.7	94.8	135.9
Average Breaking Strain	$\mu\varepsilon$	3344	3057	10650

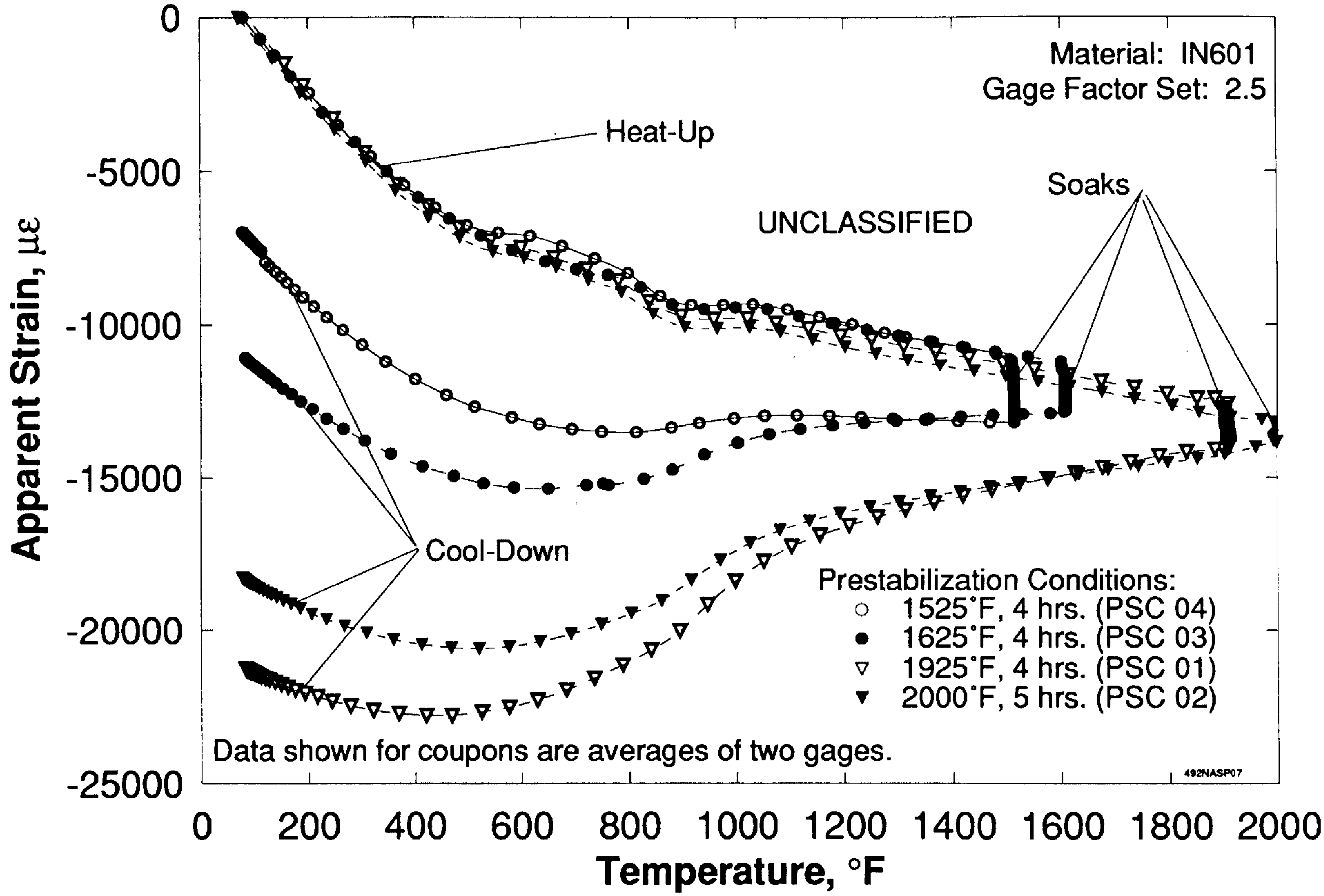
NOTES:
(1) In all cases, the flanges failed before the welds failed.
(2) Breaking Strain is calculated using the formula for elastic strain,

$$\varepsilon = \sigma / E$$

since stress-strain curves beyond the elastic range were unavailable.
(3) Numbers after flange material types are thicknesses of flanges.
(4) All flanges were spotwelded to a coupon of 65.7 mil thick ß21S.
(5) All flanges nominally 0.165 in. wide.

Coupon Number	Prestabilization Temperature (°F)	Soak Time (hours)	Test Temperature (°F)
1	2000	5	1900
2	1925	32	1900
3	1925	20	1900
4	1925	8	1900
5	1925	4	1900
6	1525	20	1500
7	1525	8	1500
8	1525	4	1500
9	1225	20	1200
10	1225	8	1200
11	1225	4	1200
12	1625	4	1200
13	1525	4	1200

BCL Prestabilization Optimization Coupon Testing

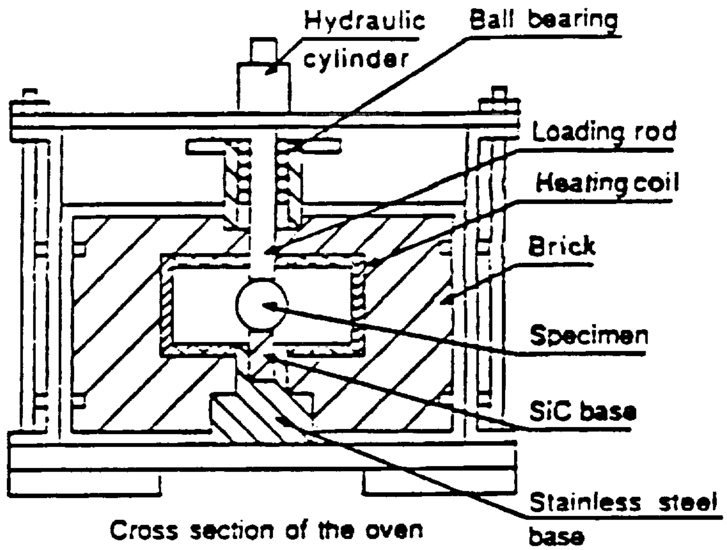


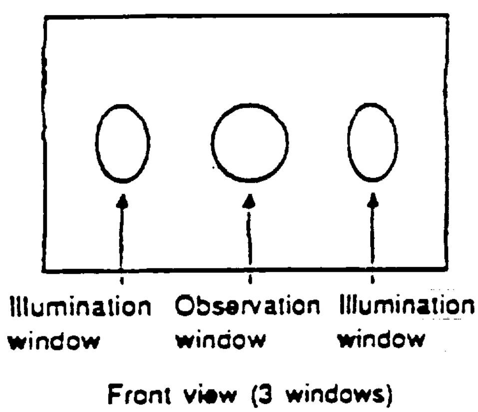
First Cycle Untreated BCL Gage Apparent Strain During Prestabilization

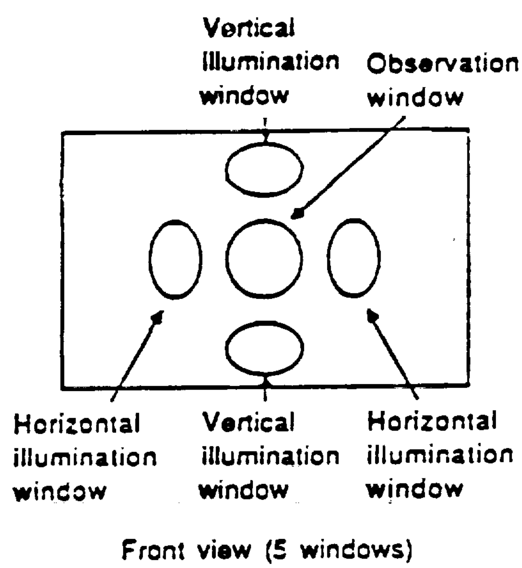
		0-4 hrs.	0 - 20 hrs.	12- 20 hrs.
1525°F	Gage 1	-127.49	-63.65	-34.13
	Gage 2	-111.74	-58.73	-33.55
	Average	-119.62	-61.19	-33.84

		0-4 hrs.	0 - 20 hrs.	10- 20 hrs.
1925°F	Gage 1	-138.58	-71.07	-39.68
	Gage 2	-129.10	-70.05	-41.46
	Average	-133.84	-70.56	-40.57

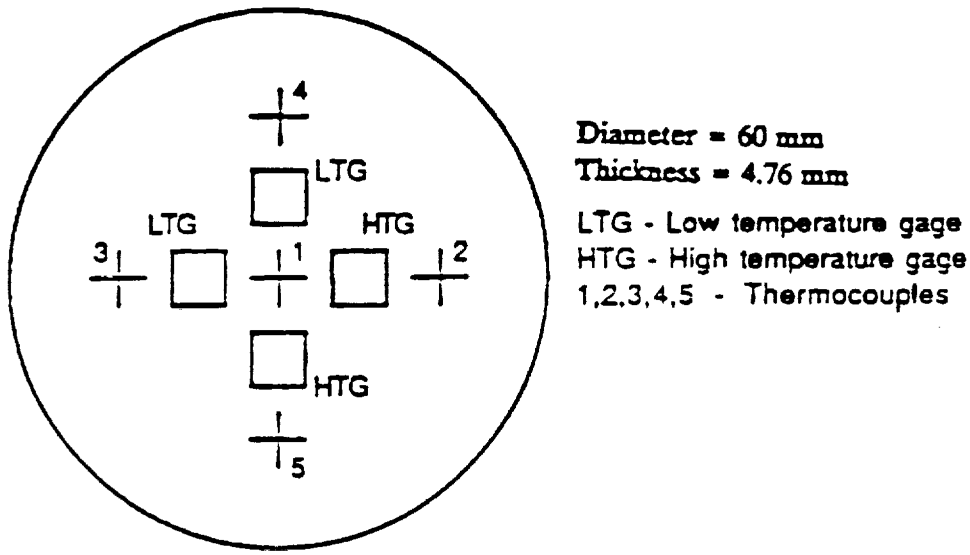
First Cycle Untreated BCL Gage Average Drift Rates During Prestabilization



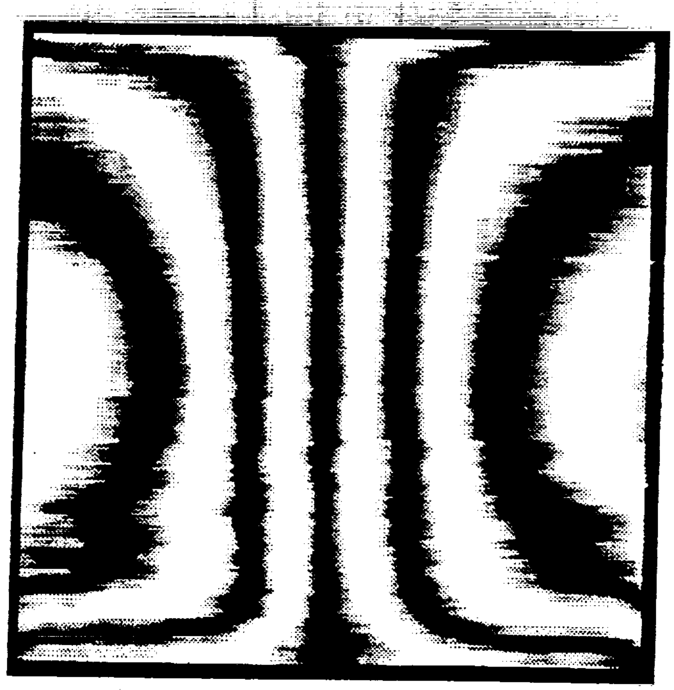




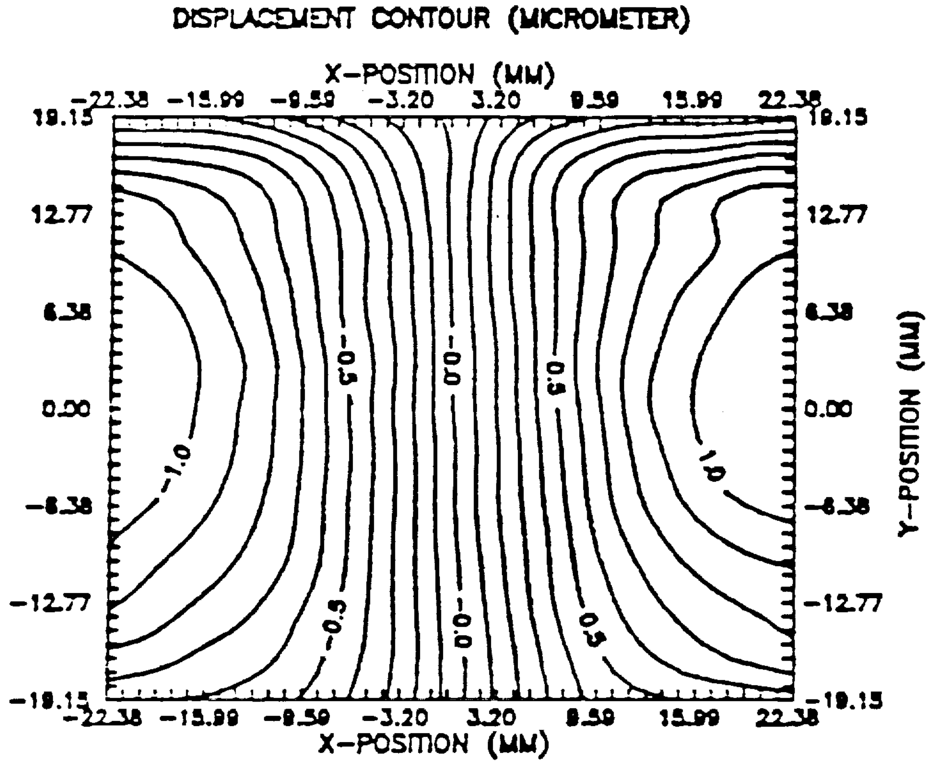
High temperature oven used to test specimens up to 1000°C.



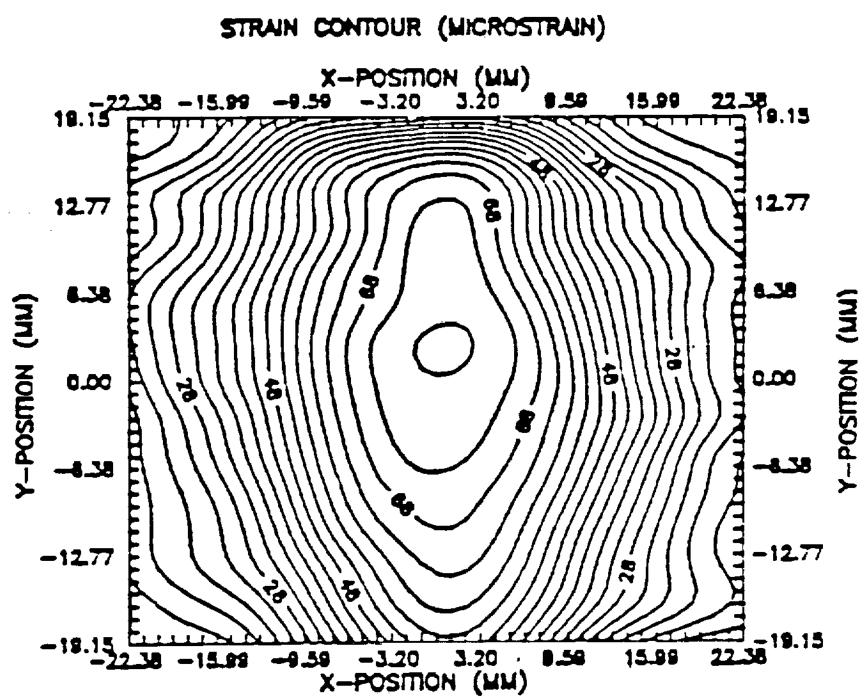
Location of thermocouples and strain gages in the disk specimen



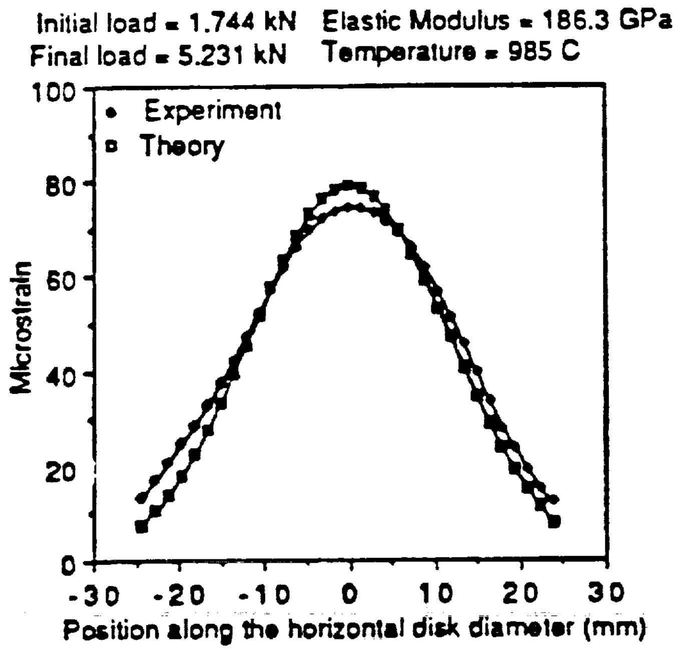
Electro-optical holographic-moire pattern (horizontal displacements) resulting from the phase averaging of 40 patterns recorded at 990°C.



Displacement contours corresponding to the pattern on bottom of page 156.



Strain contours corresponding to the pattern shown on bottom of page 156.



Comparison of theoretical and experimental results along the horizontal diameter (strains) as shown on bottom of page 157.

Optical vs. Gage

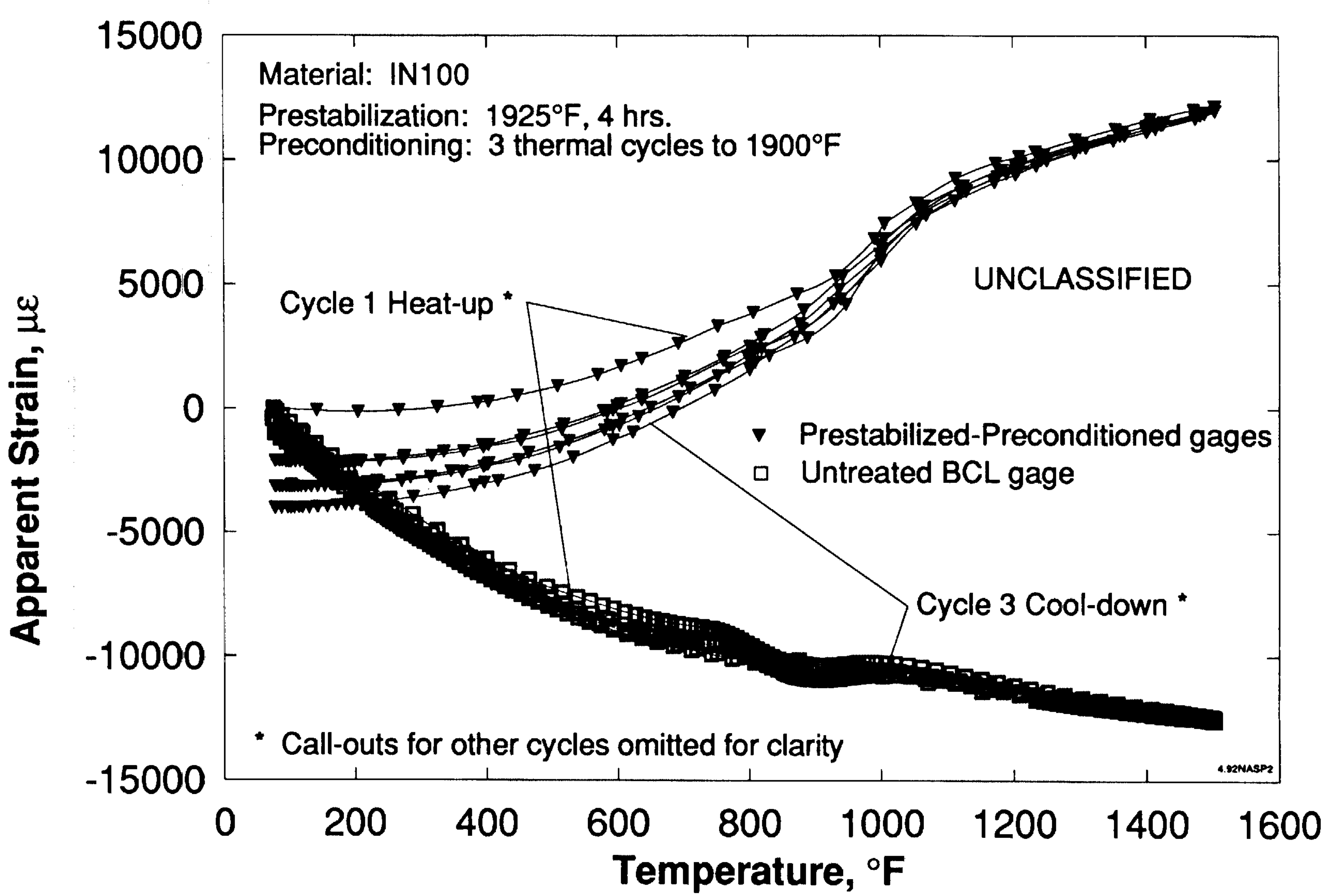
17.8 KN

Vertical Illumination and Strains

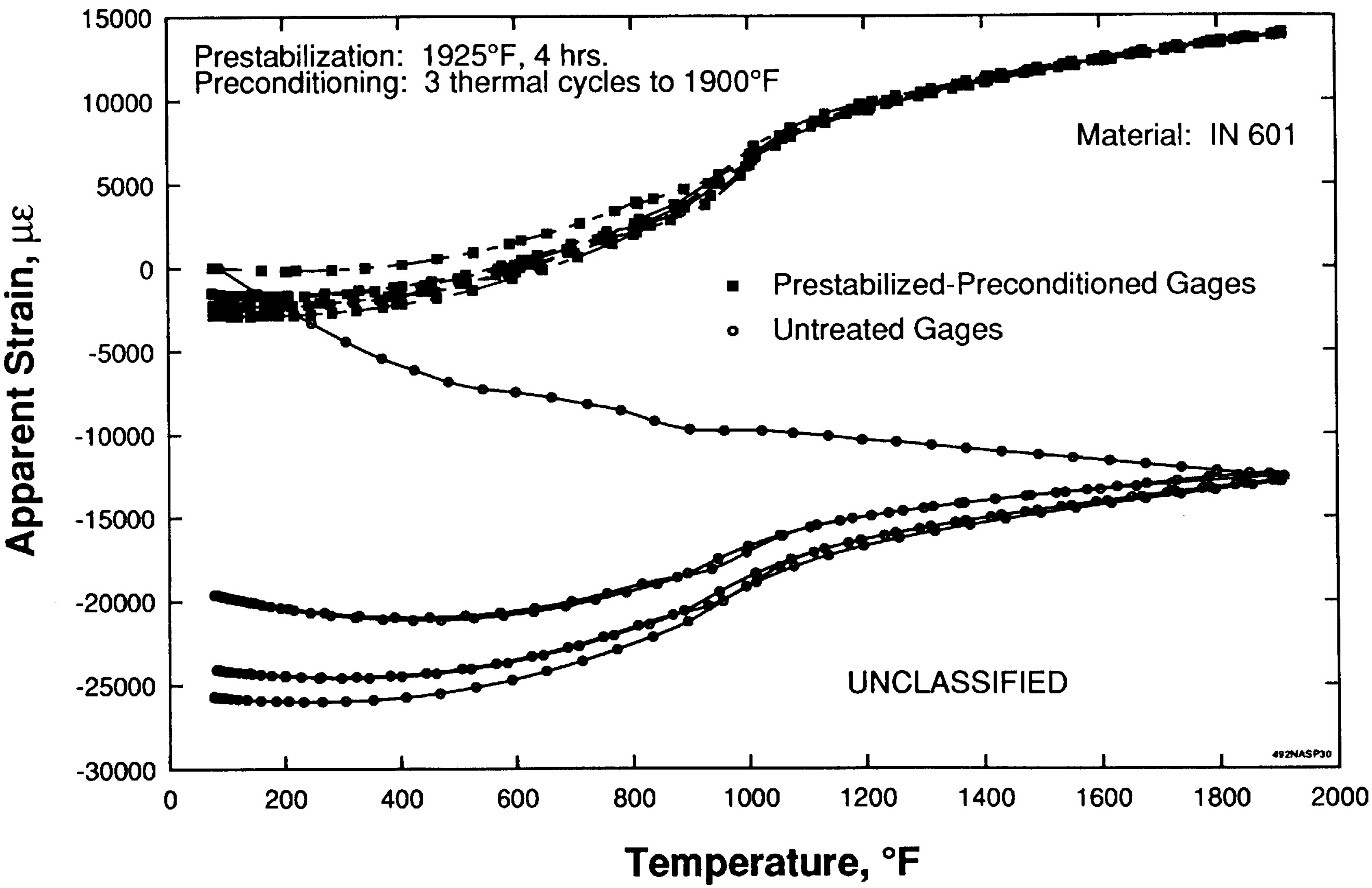
°C (°F) Temp Oven	Gage #3	Optical	% Difference Gage - Optical
23.3 (75)	-529 $\mu\epsilon$	-501$\mu\epsilon$	-5.3%
93.3 (200)	-456$\mu\epsilon$	-477$\mu\epsilon$	+4.6%
149 (300)	-496$\mu\epsilon$	-525$\mu\epsilon$	+5.7%
205 (400)	-512$\mu\epsilon$	-487$\mu\epsilon$	-4.8%
260 (500)	-499$\mu\epsilon$	-507$\mu\epsilon$	+1.6%

Optical vs. Gage

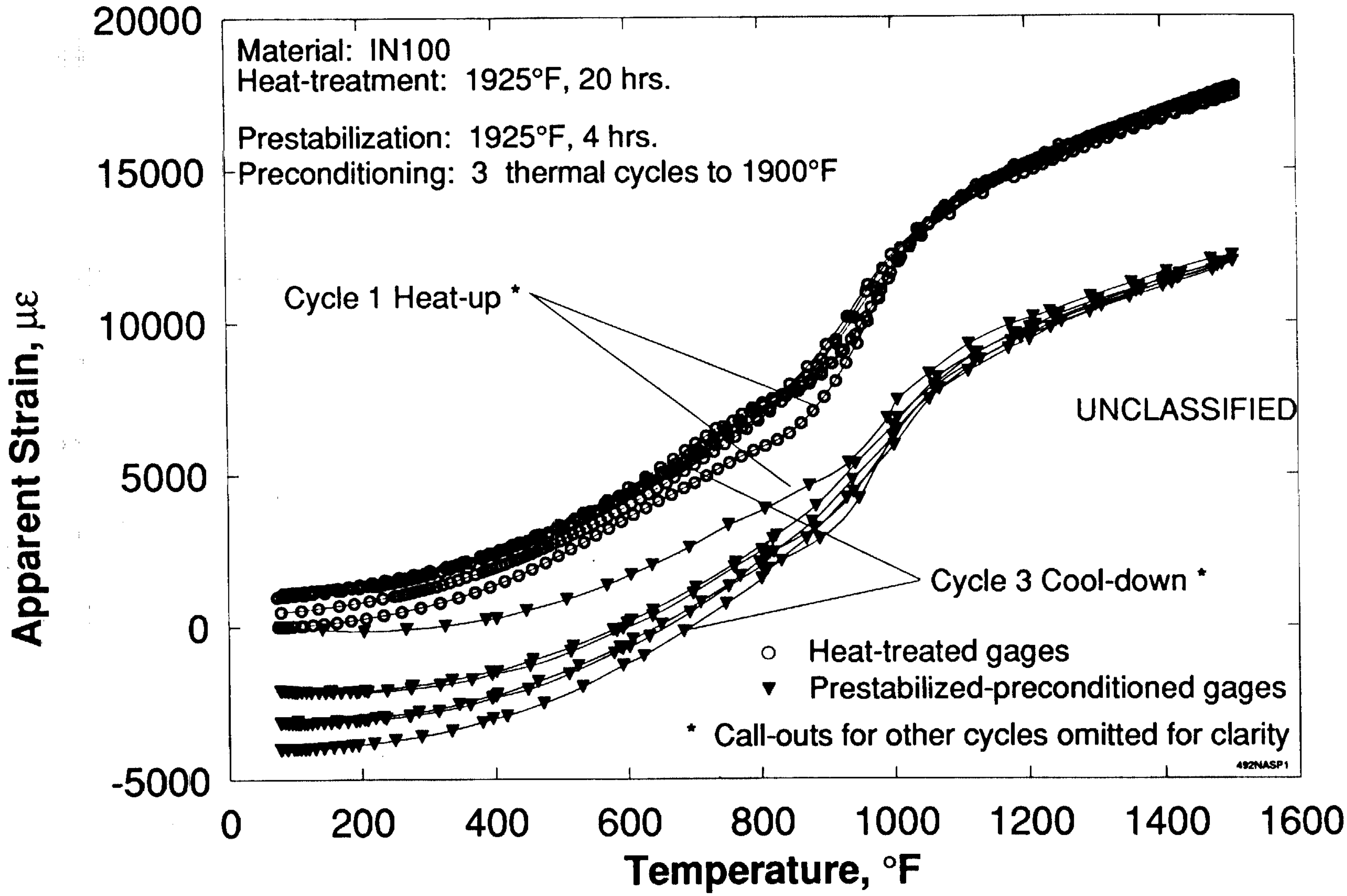
20.93 KN Horizontal Illumination and Strains			
°F Temp Oven	Gage #4	Optical	% Difference Gage - Optical
23.3 (75)	230$\mu\epsilon$	243$\mu\epsilon$	+5%
93.3 (200)	212$\mu\epsilon$	227$\mu\epsilon$	+6%
149 (300)	205$\mu\epsilon$	221$\mu\epsilon$	+7%
205 (400)	210$\mu\epsilon$	211$\mu\epsilon$	+0.8%
260 (500)	220$\mu\epsilon$	216$\mu\epsilon$	-1.5%



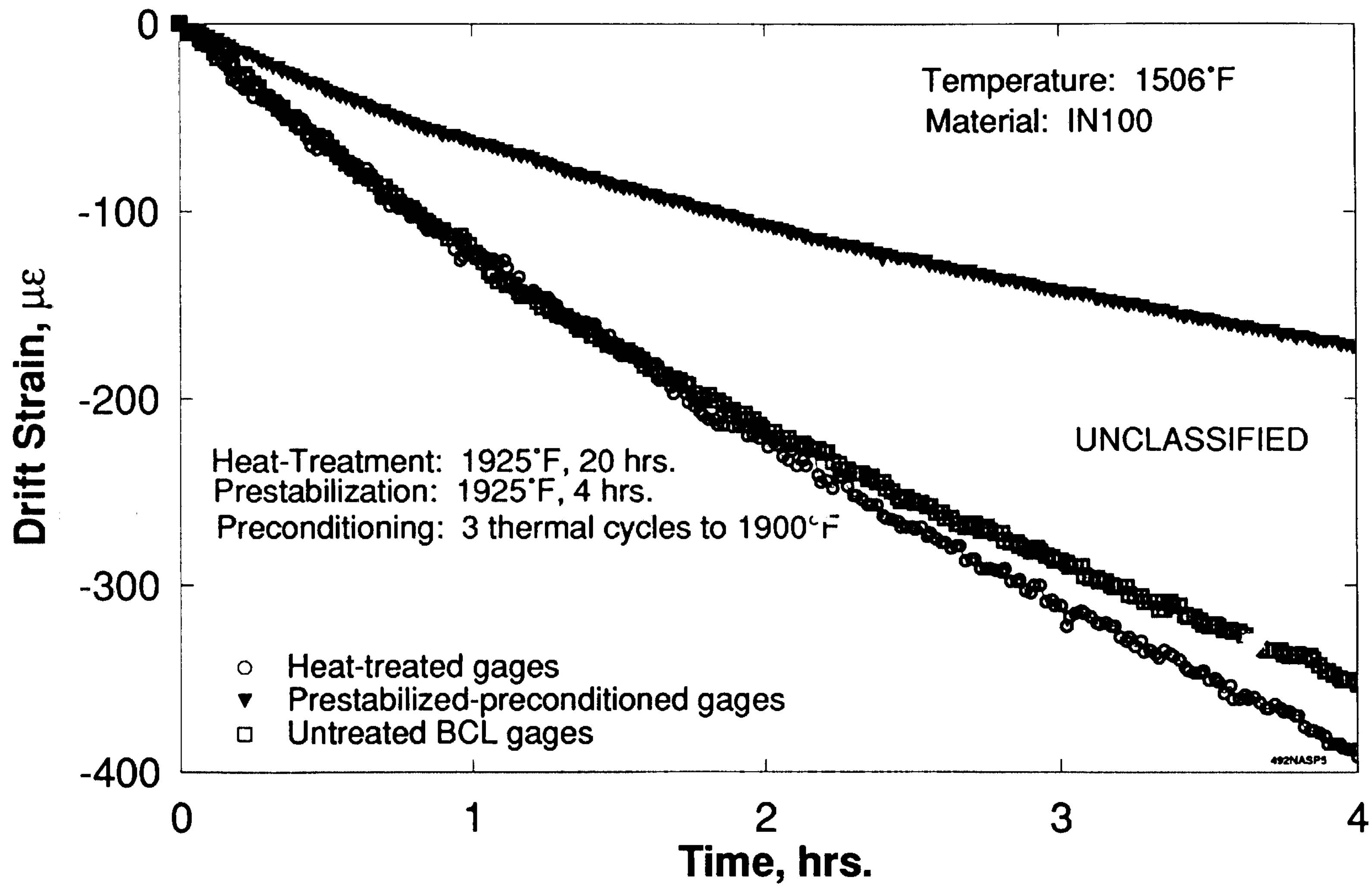
Apparent Strain of Prestabilized-preconditioned and Untreated BCL Gages



Comparison of Prestabilized-Preconditioned and Untreated BCL Gage Apparent Strains to 1900°F



Apparent Strain of Heat-treated and Prestabilized-preconditioned BCL Gages

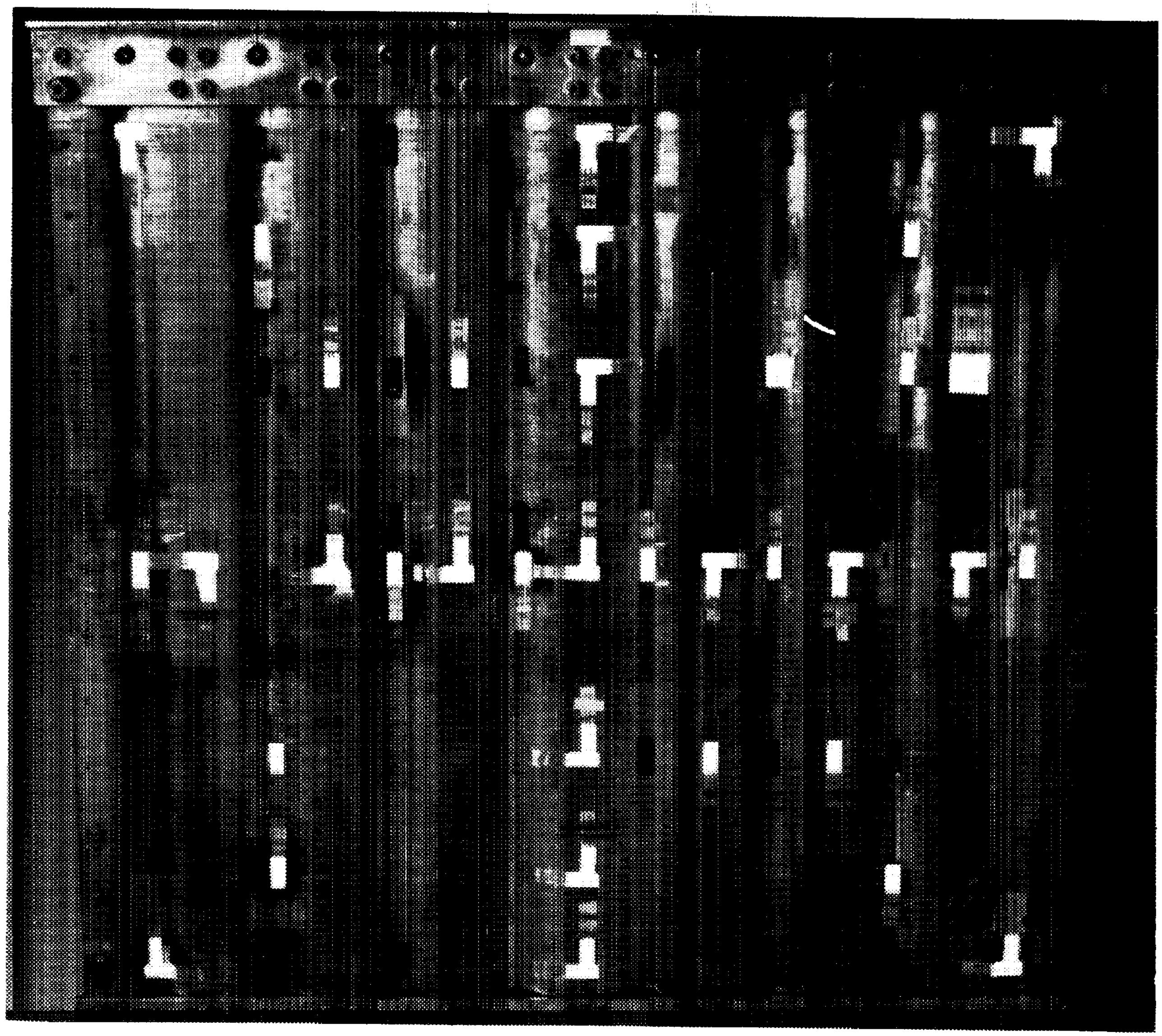


Drift Strain of Heat-treated, Prestabilized-preconditioned, and Untreated BCL gages

Temperatures, °F	BCL Gage Drift Rates, $\mu\varepsilon$/ hr	NZ-2104 Gage Drift Rates, $\mu\varepsilon$/ hr
500	25.40	16.33
1050	-26.18	-87.93
1200	-11.63	-80.63
1350	-57.48	-118.13
1500	-148.89	-181.46

Gage Factor Setting was 2.50 for both gage types at all temperatures.
Values shown are averaged for 1 hour tests.

Comparison of BCL Gage and NZ-2104 Gage Untreated Gage Drift Rates

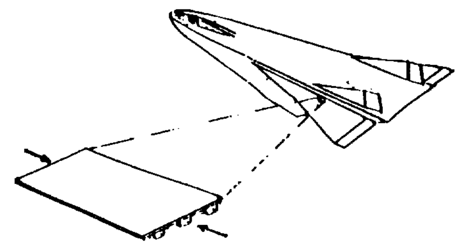


Brazed-Beaded β21S Buckling Panel. Instrumented Skin Side.

Gage Type	Expected Number of Gages	Maximum Test Temperature
NZ-2104-120L	110	1500 °F
WK-03-250BG-350	57	500 °F
PdCr (Lewis gage)	4	1500 °F
BCL-3	2	1500 °F
Modified Chinese Gage (Tom Moore's 1/2 bridge)	1	1500 °F

Gages to be Used on the Brazed, Beaded Beta 21S Buckling Panel

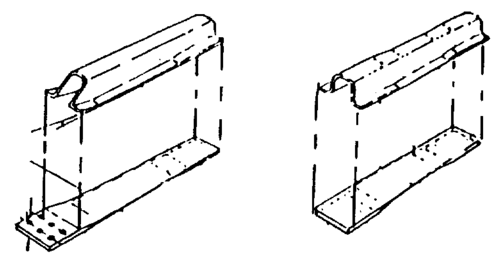
NASP Highly Loaded Stiffeners



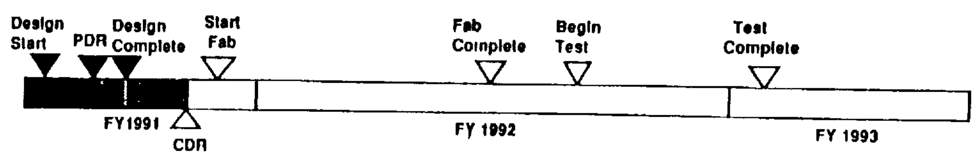
- **Represents typical mid-plane stiffener and runout region at panel ends**
- **Test Objectives**

  Validate capability of highly loaded, thick ply buildup TMC stiffener attachment and runout through testing of six articles

- **Key Requirements**
  - Design limit loads:5000 #/in axial compression/tension
  - 1500 °F maximum usage temperature
  - Thermal-mechanical fatigue



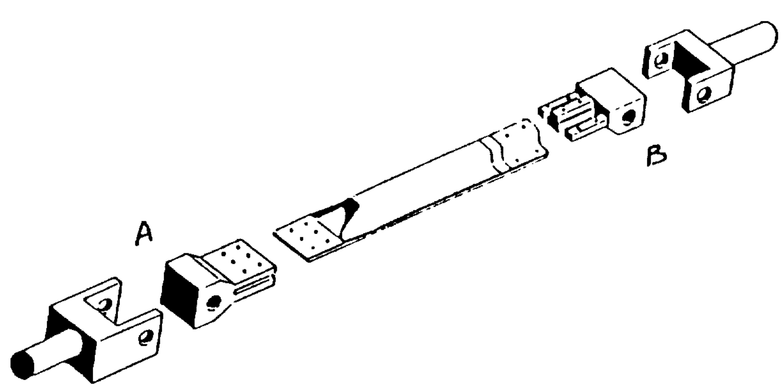
- **Major Milestones**



NASP Highly Loaded Stiffeners (U)

Test Fixture Concept (U)

(U) Simple supports into uniaxial testing machine
(U) Radiant quartz lamp heating
(U) Actively cooled clevices



VII. CONCLUDING REMARKS:

BASED ON THE MOST RECENT FINDINGS, IT APPEARS THAT:

- OBTAINING VALID FIRST-CYCLE DATA TO 1500°F MAY BE POSSIBLE, WITH THE BCL GAGE DEPENDING UPON THE OUTCOME OF CHARACTERIZATION STUDIES AND DEVELOPMENTAL ACTIVITIES NOW IN PROGRESS

- FOR STRAIN MEASUREMENTS WITH THE BCL GAGE ABOVE ABOUT 1500°F, PRESTABILIZATION AND PRECONDITIONING WILL BE REQUIRED, UNLESS THE APPARENT STRAIN OR DRIFT IS SUFFICIENTLY SUPPRESSED VIA HEAT-TREATMENT, USE OF TEMPERATURE-COMPENSATED GAGES, OR A REMOTE DUMMY GAGE SYSTEM.

- FOR STRAIN MEASUREMENTS ABOVE 1900°F, IT APPEARS THAT ONLY THE ELECTRO-OPTICAL METHODS HAVE THE POTENTIAL CAPABILITY. HOWEVER, BEFORE THESE METHODS ARE VIABLE FOR GROUND OR FLIGHT TESTING, MORE DEVELOPMENT AND VALIDATION WORK - OFF THE OPTICAL BENCH - NEEDS TO BE DONE UNDER REALISTIC FIELD CONDITIONS, AND ON MATERIALS OF INTEREST TO THE NASP AND OTHER PROGRAMS.

- IT MAY BE POSSIBLE TO PRESTABILIZE, PRECONDITION, OR PRECALIBRATE SHIM-MOUNTED OR WELDABLE TYPE GAGES PRIOR TO INSTALLATION ON THE TEST ARTICLE OR SPECIMEN - SATISFYING THE PRESENT NASP REQUIREMENT THAT NO PRESTABILIZATION BE DONE ON THE TEST ARTICLE.

- HEAT-TREATED GAGES OR PRESTABILIZED AND PRECONDITIONED SHIM-MOUNTED GAGES, OR TEMPERATURE-COMPENSATED GAGES (DUAL-ELEMENT OR FLOATING DUMMY), OR REMOTE DUMMY GAGE SYSTEMS OFFER A VARIETY OF CHOICES OR COMBINATIONS FOR EFFECTIVE SUPPRESSION OF APPARENT STRAIN. USE OF THE REMOTE DUMMY GAGE SYSTEM OR FLOATING DUMMY GAGE SHOULD ALSO SUPPRESS DRIFT STRAIN.