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Materials Research for High Speed Civil Transport and Generic Hypersonics - Composites Durability

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FOREWORD

This contractor report was prepared by the Boeing Commercial Airplane Group, Renton, Washington, under contract NAS1-20013. It covers work performed between May 15, 1993, and February 28, 1995. The contract was sponsored by the National Aeronautics and Space Administration, Langley Research Center (NASA-LaRC) as part of the Materials Development Omnibus Contract (MDOC) program. The work was performed under Task Assignment No. 10.

Portions of this work, from May 15, 1993, to October 22, 1993, were performed under Transcentury Composite Aircraft Primary Structure (TCAPS) Task 11.

Use of commercial products or names of manufacturers in this report does not constitute official endorsement of such products or manufacturers, either expressed or implied, by The Boeing Company or National Aeronautics and Space Administration.

Current program management for this task includes Ms. Heather Allen-Lilly, task leader, Mr. Dan Hoffman, task integration leader, Mr. Peter Rimbos, principal investigator, and Mr. Don Grande, program manager. Authors listed for this contractor report prepared portions of the document.

Prototype fixture concept development, design, and analysis were performed by Boeing. Integrated Technologies, Inc. (Intec) of Bothell, Washington, modified the compression prototype fixture, fabricated all test fixtures, and conducted all validation testing described herein. Thermal chambers design, fabrication, and validation testing were performed by Intec. Several of the conclusions and recommendations for future testing are based on Intec observations (refs. 1–4).

This is a multiple-year task that will continue under High-Speed Research (HSR) II, Contract NAS1-20220, Task 15, Materials Durability. Results for durability testing of composites are not included in this report. This testing will be conducted and reported under Task 15.

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GLOSSARY

ASTM	American Society for Testing and Materials
BMI	bismaleimide
CTE	coefficient of thermal expansion
DAQ	data acquisition
DiCTE	differential coefficient of thermal expansion
HAR	hydraulic-actuated reversible
HSCT	High-Speed Civil Transport
HSR	High-Speed Research
Intec	Integrated Technologies, Inc.
ksi	thousand pounds force per square inch
LaRC	Langley Research Center
LN2	liquid nitrogen
LVDT	linear voltage displacement transducer
MDOC	Materials Development Omnibus Contract
MMC	metal-matrix composite
msi	million pounds force per square inch
NASA	National Aeronautics and Space Administration
Nitinol	nickel titanium Naval Ordinance Lab (shape-memory material)
PID	proportional integral derivative
PMC	polymer matrix composite
RTV	room temperature vulcanized
TAC	thermally actuated compression
TAT	thermally actuated tension
TCAPS	Transcentury Composite Aircraft Primary Structure
TMF	thermomechanical fatigue

1.0 SUMMARY

This report documents the design, analysis, fabrication, and testing of equipment intended for use in validating the long-term durability of materials for the High-Speed Civil Transport (HSCT) project. This equipment includes thermally actuated compression (TAC) and tension (TAT) fixtures, hydraulic-actuated reversible (HAR) load fixtures, and thermal chambers. The fixtures were designed to facilitate simple and economical long-term thermal and mechanical aging testing of coupon-sized polymeric composite specimens. Implementation of large numbers of these fixtures in a single environmental chamber is intended to minimize the cost of expensive load frames and environmental chambers.

The TAC and TAT fixture designs take advantage of the coefficient of thermal expansion (CTE) mismatch of two metals (invar and stainless steel) to provide displacement-controlled load cycles in phase with slow thermal cycles. A feasibility study was conducted to select a design for this concept. From this study a prototype compression and tension fixture were designed, optimized (with the aid of a Microsoft Excel™ spreadsheet program), fabricated, and validation tested. The test results demonstrated that, for both fixtures, strains can be reliably and repeatably induced in the test specimen sufficiently high to be practical for long-term fatigue testing. The prototype fixtures are shown in figures 1.0-1 and 1.0-2. An HAR fixture was designed to accommodate tension or compression specimen testing. This fixture can mimic the performance of the thermally actuated fixtures, but is also capable of faster cycle times and higher loads.

Thermally actuated fixtures are recommended for fatigue cycling when long-term thermo-mechanical fatigue (TMF) data are required on coupon-sized tension or compression specimens. This method works best with relatively slow cycle times and works either in phase or out of phase with a significant change in temperature. Analysis of the fixture is required for each different material because the performance of the fixture will depend on the coupon size and ply orientation, as well as the specimen length. For materials with especially high CTE (>12 microstrain/°F), significant modifications to the fixture or the specimen may be required.

Two chambers were fabricated for thermal cycling TAC and TAT fixtures from room temperature to 300°F and 350°F. Each chamber contains 25 cells with modular doors for individual cell access. A 100-cycle validation test of one chamber filled with 25 fixtures demonstrated that a uniform temperature profile could be maintained throughout the cycle.

A third 25-cell chamber was constructed for the dual purpose of thermal cycling HAR fixtures, as well as the TAC and TAT fixtures. Chamber validation involved a thermal cycle-hydraulic load equivalence test, to verify that hydraulics can mimic the thermal loads, and a spectrum test that included load spikes.

Long-term durability testing plans for polymer matrix composite (PMC) specimens are included in this report. Material types, prestrain and maximum strain conditions, and instrumentation are outlined for a 1,000-thermal-cycle test using TAC and TAT fixtures in the 300°F and 350°F chambers.

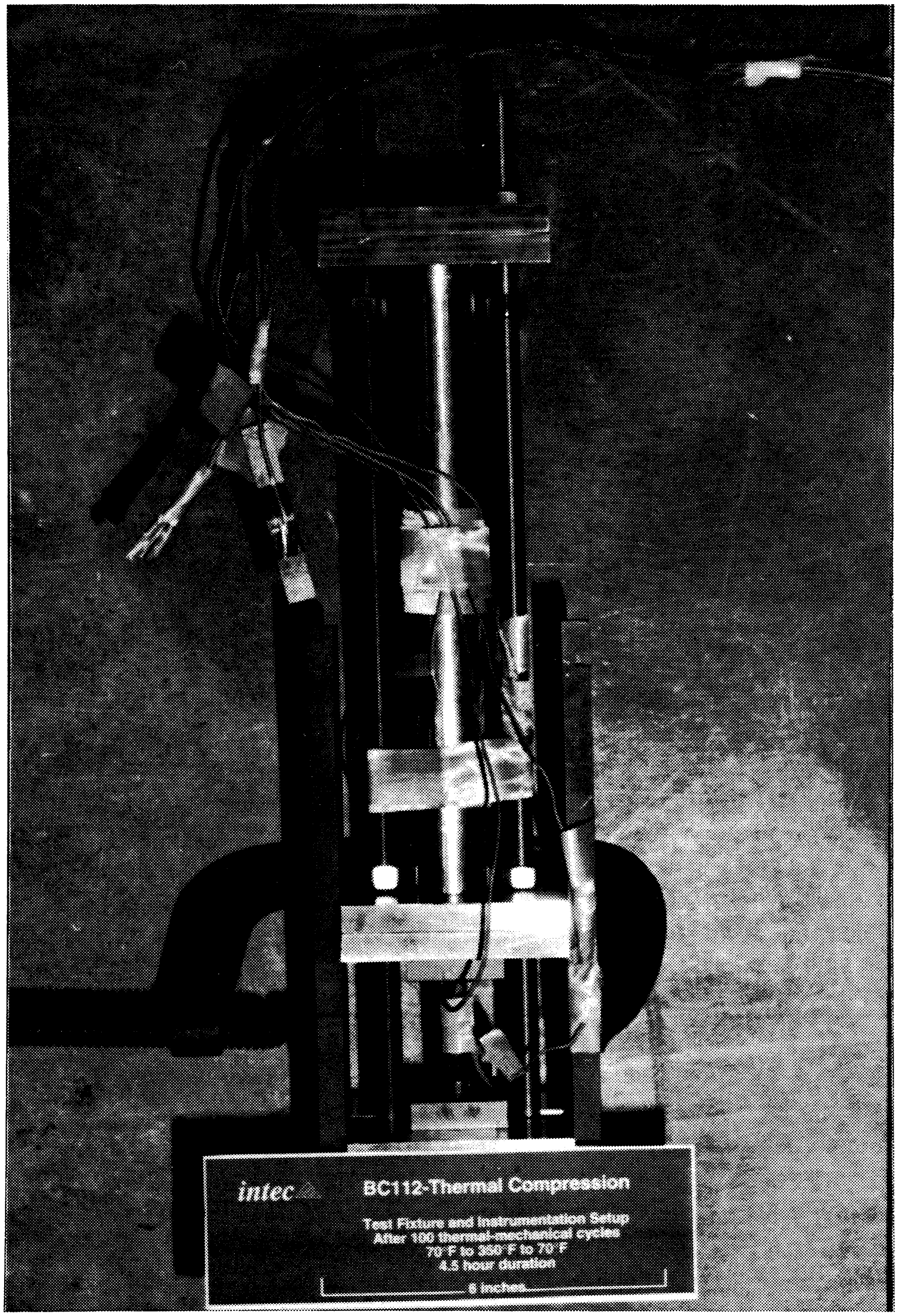


Figure 1.0-1. Thermai Compression Fixture Setup

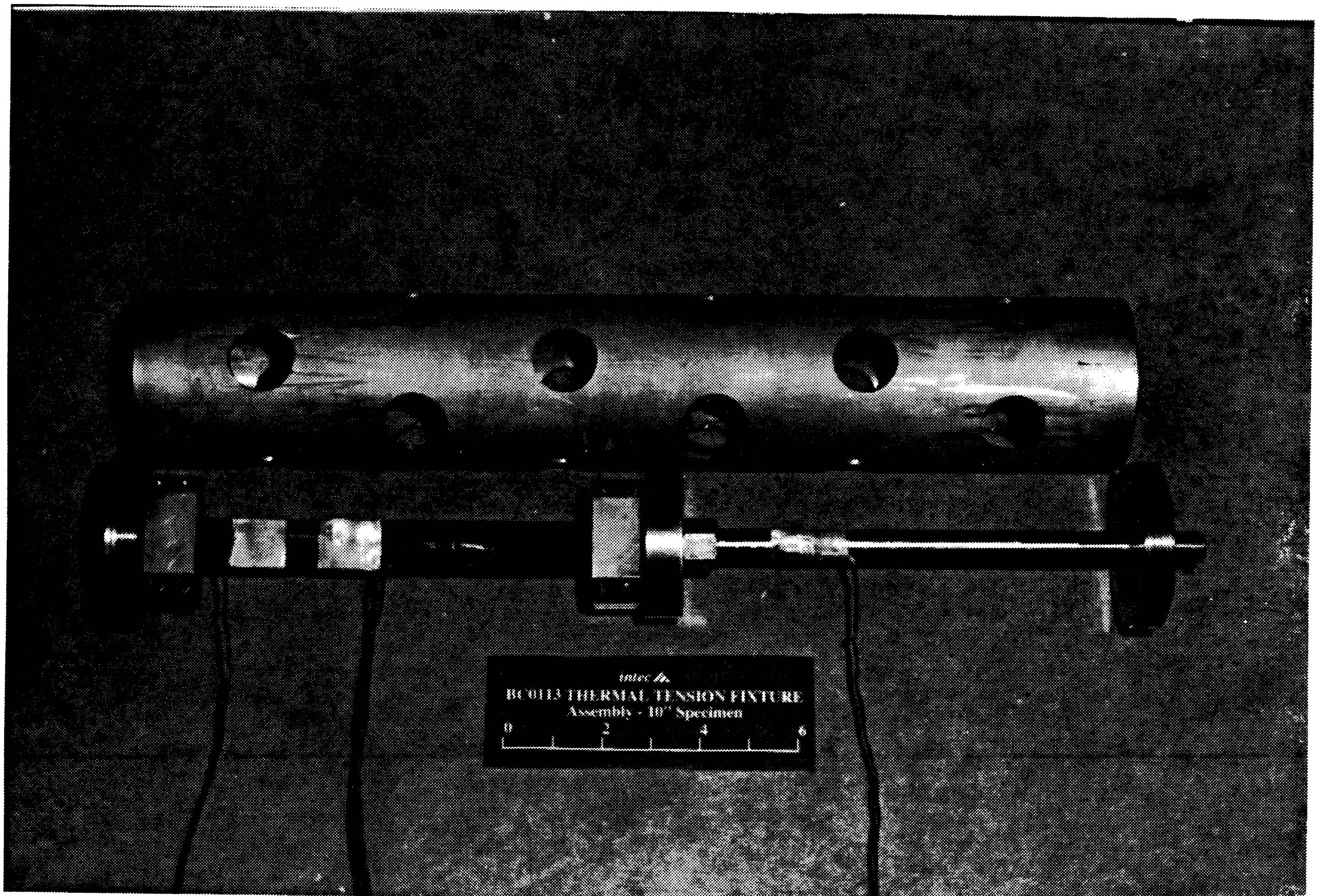


Figure 1.0-2. Thermal Tension Fixture Setup

2.0 INTRODUCTION

2.1 HSCT DURABILITY REQUIREMENTS

The HSCT program is currently looking at three families of materials for use in building the airplane. These include aluminum, titanium, and PMCs. Any material that will be selected for use must be able to survive a 60,000-hr life at elevated temperatures. (The adiabatic wall temperature for a mach 2.4 cruise speed is 350°F). Figure 2.1-1 shows proposed vehicle envelope requirements for the HSCT, including those concerned with the durability issue. Figure 2.1-2 shows the latest thermal profiles for a Mach 2.4 version of the airplane.

An extensive program to provide environmental durability test data and life-prediction methodology has been established to ensure that any material (PMC or metal) is viable for the HSCT. New aluminum and titanium alloys show potential for meeting the durability requirements but have not yet been fully tested. However, trade studies show that the airplane will pay a weight penalty if these are the primary materials.

The use of PMCs as primary structure could greatly reduce aircraft weight, and HSCT program objectives include developing composites that possess high-temperature and long-term durability capabilities for up to two lifetimes—120,000 hr at temperature. Even more extensive testing will be required to ensure the environmental durability of this material class.

Design Element	Requirement
Mach number	2.0 to 2.4
Flight length, hr	4.5
Engine fuel type	Conventional
Number of flights	30,000
Time at cruise, hr	60,000
Range, nmi	5,000 to 6,500
Altitude, ft	60,000 to 70,000
Noise	FAR 36, Stage 3
Lifetime, hr	72,000
Temp limit, °F	<350 (400 dive)

Figure 2.1-1. Vehicle Design Requirements

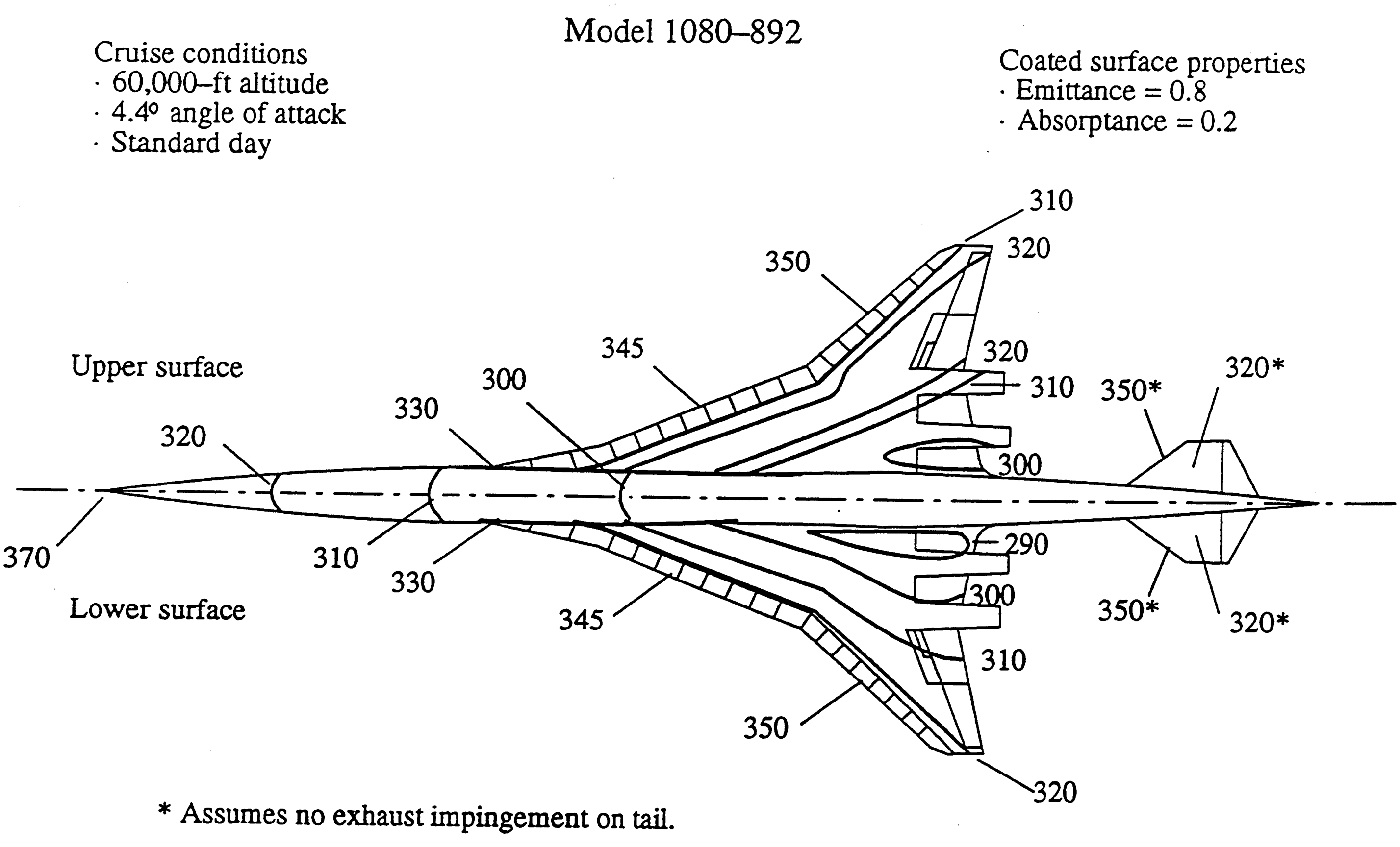


Figure 2.1-2. Study Vehicle Configuration and Thermal Profiles

2.2 PMC DURABILITY TEST REQUIREMENTS

The HSR program has adopted a "building-block" approach to develop this material and to determine its aging characteristics. The first part of this approach consists of selecting three to four representative PMC materials for insertion into a long-term test program. This program would be designed to validate predictive methodologies for material response, residual strength, and life. Approximately 6,000 test coupons per material will be subjected to various tests including open-hole compression, open-hole tension, compression after impact, unnotched compression, unnotched tension, toughness, bearing, and microcracking tests under various load and temperature conditions. Many of these tests must be conducted simultaneously, thereby requiring a large number of test setups (18,000 to 24,000). Because time-at-temperature effects are expected to be significant, much of the testing must be performed for long periods of time. The cost of tying up expensive hydraulic load apparatus for 7+ years is prohibitive. This equipment is better used for more complex loading such as spectrum fatigue where no alternatives currently exist. To keep the cost of this program to an acceptable level, a series of low-cost test fixtures must be developed that will thermomechanically load the specimens and be able to maintain this capability for the duration of the test program.

The second phase of the building-block approach involves testing elements. One or two of the candidate PMC materials will be selected based on their ability to perform in the HSCT environment. The elements will consist of crippling specimens, padups, flanges, stiffeners, and a host of other specimen types. The number of these will be on the order of 2,000 to 3,000 specimens per material, significantly less than in the first phase. With the experience and data obtained from previous testing, low-cost test fixturing will be developed that will thermomechanically load the elements in a similar fashion as before. A portion of both the phase 1 and 2 tests specimens will also be used to help develop and validate an accelerated test methodology in order to quickly screen new materials introduced into the program. These accelerated tests will be validated by ongoing real-time testing.

The third portion of the approach involves testing subcomponents and components manufactured from the downselected PMC material (fig. 2.2-1). This testing will serve to validate the manufacturing process, predictive aging methodology (scaled up to assess structural behavior), and analysis methods developed in parallel efforts.

An approach for durability testing of composites at the coupon and element level was developed under this task for the long-term testing of composites undergoing thermal cycling. It takes advantage of the difference in CTEs of two dissimilar metals (steel and invar) to provide the displacement-controlled compressive or tensile load cycles in phase with thermal cycles.

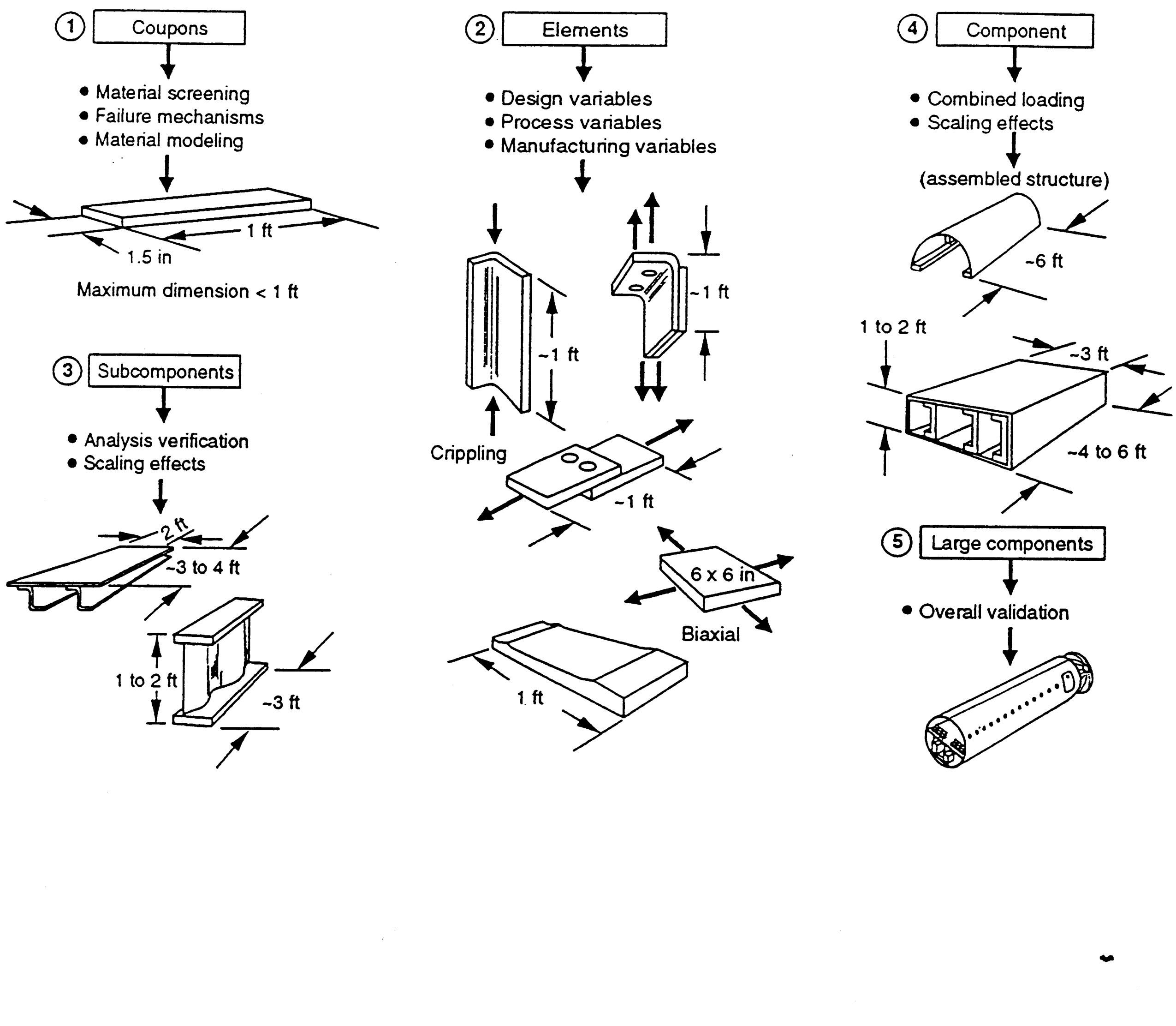


Figure 2.2-1. Structural Hardware Definitions

3.0 OBJECTIVES

The long-term objective of this task is to study composite durability for HSCT applications. The short-term objectives of this task were to develop and fabricate low-cost single coupon test fixtures and thermal cycling chambers and perform validation tests of these systems. Fixture designs were to be based on the differential coefficient of thermal expansion (DiCTE) concept. Low-cost modular hydraulic, pneumatic, or mechanical fixtures were also to be designed and fabricated to demonstrate equivalence to the DiCTE fixture test results. Testing, using design of experiments, was to focus on determining the key variables and main interactions between time, temperature, environment, and stress (or strain).

The technical approach included fixture concept definition and downselection, fixture design and analysis, fixture fabrication, and validation testing. Thermal cycling chambers and data acquisition systems were designed and fabricated to perform composite durability testing with thermal and hydraulic fixtures.

The specific tasks performed on this program include the following:

a. Develop fixturing concepts and accompanying test coupons.

b. Define design criteria and performance specifications.

c. Downselect and perform detailed design, analysis, and sensitivity studies on two prototype fixture designs.

d. Manufacture a minimum of one TAT and one TAC prototype fixtures.

e. Design an HAR load fixture and manifold system.

f. Perform testing as required to ensure correct load levels and repeatability.

g. Fabricate 16 TAT, 16 TAC, and 4 HAR fixtures.

h. Design, manufacture, and test three thermal cycling chambers: Nos. 1 and 2 for cycling the TAT and TAC fixtures from room temperature to 300°F or 350°F, and No. 3 for the dual purpose of cycling either the TAT, TAC, or HAR fixtures from room temperature to 300°F or 350°F.

i. Plan for long-term thermal cycling tests of available HSCT candidate composite laminates.

4.0 THERMALLY ACTUATED FIXTURES

4.1 FIXTURE CONCEPTS

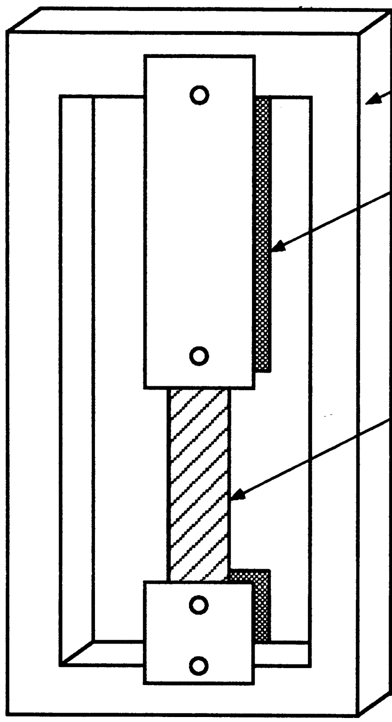
Fixture concept development began with brainstorming and a review session that yielded more than 15 potential concepts. These concepts were sketched and described in sufficient detail for further evaluation. The majority of these concepts are "strain controlled" in nature. Many of these concepts represented variations on a theme to accommodate different specimen geometries. Figure 4.1-1 lists these concepts.

Concept	Description
1	Inline driver compression
2	Inline driver tension
3	Heated driver compression
4	Cooled driver tension
5	Picture frame compression
6	Expanding ring uniform tension
7	Tube tension
8	Tube compression
9	Hoop tension
10	Off-angle tension tube
11	Off-angle compression tube
12	High-CTE polymer compression
13	High-CTE polymer tension
14	Unbalanced torsion tube
15	Nitinol driver tension

Figure 4.1-1. Concept List

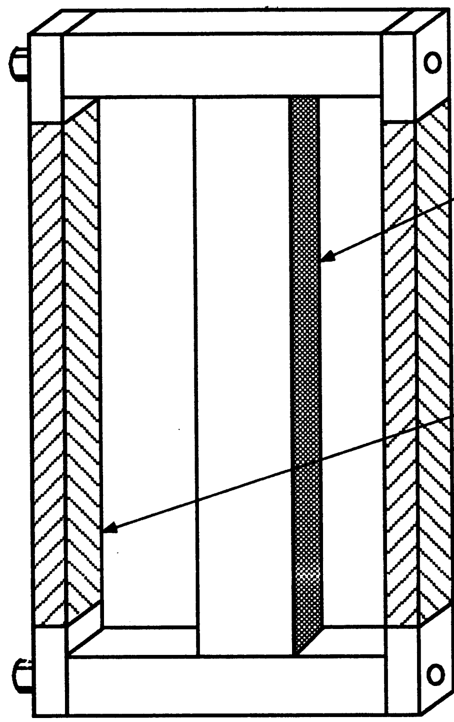
Work also was performed on identifying failure modes for each fixturing concept and determining general fixturing requirements and constraints (e.g., test fixture margin of safety, minimum load/strain capability repeatability limits, allowable drift over time, temperature capability) and downselection criteria (e.g., volume, projected cost, ease of adjustability, thermal mass).

An initial downselection (to six concepts) based on qualitative assessment of ability to provide useful data and potential functional difficulties was performed. Following this activity, preliminary sizing, capabilities, volumes, costs, and specimen types and potential output data were developed for each of the promising concepts. Sketches and detailed descriptions (including key features, potential driver and frame materials, advantages, and disadvantages) were produced. Three typical examples are shown in figures 4.1-2, 4.1-3, and 4.1-4.



General Description and Key Features:
This concept uses a high-CTE driver in series with the specimen. A low-CTE frame is connected in parallel to this combination as shown in the figure above. The frame can be monolithic, as shown, or consist of any number of low-CTE rods connected (bolted) to upper and lower base plates. A center base plate (between the driver and specimen) that slides on the rods may be added so that the specimen may be properly gripped.
Possible Materials:
Drivers: stainless steel, zinc, aluminum, Nitinol (with modified design), and others
Frame: invar, low-CTE metal-matrix composites (MMC), and others
Potential Advantages:
Simple; version with bolted base plates is inherently adjustable; tabbed specimens not required.
Disadvantages and Concerns:
Frame materials are relatively expensive; difficulty in achieving specimen edge fixities to test long (>4 in) or thin (16 plies or less) specimens; expensive grips may be required to adequately distribute load and provide end fixity.
Data and Specimen Types:
Useful for testing composite specimens that are less than 4 in long and greater than 16 plies thick in cyclic unidirectional compression loading (in combination with inphase cyclic temperature); exposure to moisture, fluids, gases, and partial vacuums or increased pressures is also possible.

Figure 4.1-2. Concept No. 1: Thermal Strain Compression (Simple)



General Description and Key Features:
This concept uses a high-CTE driver in parallel with two specimens. A low-CTE frame is connected in parallel to this combination as shown in the figure. Driver and base plate may be integrated or separate. A low-CTE filler plate may be used to connect a short specimen to a longer driver to obtain sufficient strain values. Analysis pending.

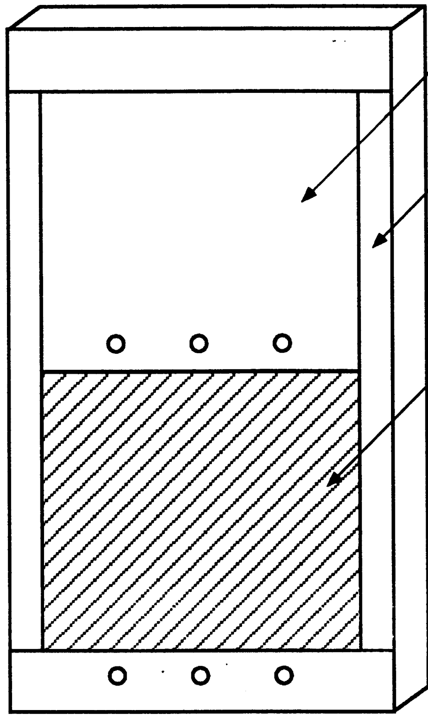
Possible Materials:
Drivers: stainless steel, zinc, aluminum, Nitinol (with modified design), and others
Frame: not applicable

Potential Advantages:
Simple; potentially very efficient (low volume); no frame required.

Disadvantages and Concerns:
Difficulty achieving balance if specimen stiffnesses degrade at different rates; adjustability unknown (dependent on exact connection of specimens to base plates); thick driver with high thermal mass may be required; tabbed specimens or expensive "wedge" grips may be required to adequately distribute load.

Data and Specimen Types:
Useful for testing composite specimens in unidirectional tension loading (in combination with inphase cyclic temperature); exposure to moisture, fluids, gases, and partial vacuums or increased pressures is also possible; no restrictions on length (some modification may be required for short specimens).

Figure 4.1-3. Concept No. 2: Dual Specimen Tension



General Description and Key Features:
This concept uses a high-CTE driver/frame that surrounds the specimen (panel) on three sides to produce biaxial tension loading on a composite panel. A low-CTE load adjustment plate may be used in conjunction with the high-CTE driver/frame to increase the applied strain in one direction. Varying the dimensions or material of this adjustment plate can change the relative magnitude of the x and y direction loads. Bolted attachment is likely on all sides. Analysis pending.

Possible Materials:
Driver/frame: stainless steel, zinc, aluminum, and others
Adjustment plate: many options—invar to steel

Potential Advantages:
Simple way to get various biaxial data; frame materials are relatively inexpensive.

Disadvantages and Concerns:
Tabbed specimens may be required; uniform load distribution may be difficult to achieve; bolted specimen connection could cause excessive creep in bearing.

Data and Specimen Types:
Useful for testing composite panels under biaxial tension loading (in combination with inphase cyclic temperature); exposure to moisture, fluids, gases, and partial vacuums of increased pressures is also possible; no restrictions on panel size.

Figure 4.1-4. Concept No. 5a: Picture Frame Tension

Two potentially suitable load application concepts were investigated. One used a DiCTE driver and the other used a tubular shape memory alloy driver. Both of the concepts could theoretically use stiff springs to create a "quasi-load-controlled" fixture. Load-controlled fixtures provide a constant load to the specimen that is insensitive to specimen stiffness changes caused by viscoelastic responses (creep/recovery) or mechanical damage. Actual redundant aircraft structure (i.e., skins, spars, etc.) behave in a manner that falls between load controlled and strain controlled. By using long, stiff springs that are relatively insensitive to small changes in displacements caused by specimen creep and so forth, a normally strain-controlled design can be converted to a quasi-load-controlled design. Using Belleville spring washers for this function would allow tailoring of the spring length and spring constant; however, springs possessing the required force and displacement characteristics have not been located.

The shape memory alloy concepts used 55 Nitinol alloy for the driver material. Nitinol (nickel titanium Naval Ordinance Lab) is an alloy consisting of roughly equal parts of nickel and titanium. One interesting characteristic of this formulation is that it may be "trained" (annealed and prestressed) such that it undergoes a Martensitic phase transformation when raised above a transition temperature (approximately 210°F). At this temperature the part attempts to return to its "trained" shape. Materials that exhibit this behavior are known as "shape memory alloys."

A truly load-controlled fixture concept was developed using this alloy. The scheme used the Nitinol to support a weight. Above the transition temperature, it shortens so that it no longer provides support and allows the weight to load the specimen. Other concepts were quasi-load controlled. The following paragraph contains a general description of how these concepts would operate.

At the transition temperature, the driver material changes phase. At this time, the material strains 3% (i.e., gets 3% longer) and builds up some internal stresses. Because this is much greater than the strain required to fail the specimen, most of this strain must be absorbed by something other than the specimen. In this fixture concept, this function is accomplished by springs. In addition, the springs serve another critical function—they recompress the Nitinol. After the temperature of the Nitinol again drops below the transition temperature, it must be recompressed so that it may repeat the cycle. This recompression strain must be 1.5% to 4.0% for the Nitinol to return to its former phase. Hysteresis problems would be encountered if the strain exceeded 4%. This strain range would require a great amount of load if the modulus of the material in this state were identical to the initial elastic modulus of 4.5 msi. In this phase, however, the material has deformed into the "pseudoplastic" range and its secant modulus at 2% strain is only 1.0 msi, resulting in a much lower load required to recompress the driver. The pseudoplastic region on the stress-strain curve is equivalent to the plastic region, except that the strain is recoverable by means of the phase transformation (whereas plastic strain is generally considered nonrecoverable).

The sizing of the Nitinol driver requires keeping the cross-sectional area of the driver as small as possible (to keep the recompression force reasonable), while avoiding a stability failure in the driver itself. The driver is especially prone to this type of failure because it is operating in the pseudoplastic region. If the initial heat treatment and recompression can be properly performed, this transition has been shown to be repeatable for an indefinite number of cycles. Many of the properties of the Nitinol show a strong dependence on the exact composition and heat-treat of the alloy, including recompression stress. To determine the recompression stress of a Nitinol driver, a prototype cylindrical Nitinol tube was obtained. Initial analysis of the tube indicated that the force required to recompress the Nitinol was unacceptably high (32 ksi) for our sample. This results in a combination of spring constant and deflection that is difficult to achieve with either helical springs or Belleville spring washers.

Although acceptable helical springs were found, the wire diameter was an inch or more. This resulted in greater fixture volumes and complexity than those for purely DiCTE-driven fixtures, even though the Nitinol driver is very small. Based on these results, the modification of the current fixture for use with the Nitinol driver has been postponed until a more viable concept emerges.

Initial analysis and optimization of fixture design No. 1, the strain-controlled DiCTE-driven concept illustrated in figure 4.1-2, indicated that this design was potentially viable and would be included as one of the downselected designs. Using a previous Boeing fixture design along with available hardware and materials, a prototype of this fixture was inexpensively constructed. It consisted of a stainless-steel driver of 1.5-in diameter, two threaded invar frame rods (0.5-in diameter), steel endplates and midplates, and simple 0.5-in grip blocks.

This prototype was used to verify analytical results and can act as a testbed to assess the viability of conventional and innovative driver materials. A computerized analysis tool was designed and adapted to perform preliminary sizing of all selected concepts and was expanded to include limited analysis for material cost and thermal mass. Following this analysis, a summary of capabilities, volumes, rough material costs, thermal mass, and specimen types and potential output data was developed for each remaining design.

Using a numerical optimization feature of the Excel spreadsheet, optimized fixture designs for a single-specimen, strain-controlled compression fixture (fig. 4.1-2) were generated for (1) minimum fixture volume, (2) minimum fixture material cost, (3) minimum thermal mass, and (4) maximum strain. Results are shown in figures 4.1-5, 4.1-6, 4.1-7, and 4.1-8. One interesting result is that the optimized fixtures for volume, thermal mass, and material cost are all very similar, and the primary difference between these designs and the current prototype is the driver diameter (1.5 in for the prototype versus approximately 0.5 in for the optimized designs). Another interesting result is that a fixture can be produced that would provide over 9,500 microstrain within a 500-in^3 volume and 24-in length constraint. The material cost of this fixture, however, is over 10 times the current prototype. The analysis tool is described further in the following section.

SUMMARY INFORMATION

CURRENT FIXTURE - #1

PERFORMANCE		GEOMETRY		STRESS / MARGINS	
FIXTURE MATL COST:	41.50	FIXTURE HEIGHT=	15	LOAD=	1920.24
FIXTURE VOLUME=	141.90	DRIVER HEIGHT=	11	DRIVER BUCKLING=	97.52
SPECIMEN STRAIN=	2521	SPECIMEN LENGTH=	4	SPECIMEN BUCKLING=	3.98
FIXTURE MASS=	9.18	ENDPLATE THKNS=	0.5	DRIVER YIELD (cys)=	20.47
FIX DIFFUSIVITY/VOL.	0.09	MIDPLATE THKNS=	0.5	FRAME YIELD (tys)=	1.64
ADJUSTABILITY	EASY			FRAME FATIGUE=	2.17
DRIFT	?	DRIVER DIAMETER=	1.5	DRIVER FATIGUE=	32.46
		FRAME ROD DIA.=	0.44		
		SPECIMEN THICKNESS=	0.179		
		SPECIMEN WIDTH=	0.5		
		BASEPLATE LENGTH=	3		
		BASEPLATE WIDTH=	2.5		

TEMPERATURE DATA

Tmin=	75
Tmax=	350
Delta T=	275

MATERIAL PROPERTIES

	MODULUS (msi)	CTE(x 10-6]	MATL
DRIVER	28.00	8.90	STEEL
FRAME	20.50	1.10	INVAR
SPECIMEN	8.50	1.20	PMC
ENDPLATES	28	8.9	STEEL

1. CTE OF ENDPLATES AND MIDPLATE WERE NOT INCLUDED IN INDUCED STRAIN
   CAN ESTIMATE EFFECTS OF PRESENT FIXTURE BY ADDING END + MIDPLATE THICKNESSES TO DRIVER LENGTH

2. EFFECTIVE WIDTH FOR BEAM BENDING OF ENDPLATES ASSUMED TO BE 0.5 INCHES

3. ESTIMATED VOLUME ASSUMES: (1) 0.5 IN. BETWEEN DRIVER, RODS, SPECIMENS AND PLATE EDGES
   (2) .06 ADDED FOR FRAME THREADS, (3) MIDPLATE THICKNESS=0.5
4. CONSTRAINTS: VOLUME<500 IN.^3, LENGTH<24 IN., STRAIN>2500, MARGINS OF SAFETY>0.

Figure 4.1-5. Summary Information for Current Fixture No. 1

SUMMARY INFORMATION

VOLUME OPTIMIZED FIXTURE - #1

PERFORMANCE		GEOMETRY		STRESS / MARGINS	
FIXTURE MATL COST:	17.56	FIXTURE HEIGHT=	12.91	LOAD=	1904.00
FIXTURE VOLUME=	51.39	DRIVER HEIGHT=	8.91	DRIVER BUCKLING=	0.00
SPECIMEN STRAIN=	2500	SPECIMEN LENGTH=	4.00	SPECIMEN BUCKLING=	4.02
FIXTURE MASS=	2.83	ENDPLATE THKNS=	0.66	DRIVER YIELD (cys)=	0.76
FIX DIFFUSIVITY/VOL.	0.03	MIDPLATE THKNS=	0.50	FRAME YIELD (tys)=	1.42
ADJUSTABILITY	EASY			FRAME FATIGUE=	1.91
DRIFT	?	DRIVER DIAMETER=	0.43	DRIVER FATIGUE=	1.74
		FRAME ROD DIA.=	0.42		
		SPECIMEN THICKNESS=	0.179		
		SPECIMEN WIDTH=	0.50		
		BASEPLATE LENGTH=	1.91		
		BASEPLATE WIDTH=	1.50		

TEMPERATURE DATA		MATERIAL PROPERTIES			
			MODULUS (msi)	CTE(x 10-6)	MATL
Tmin=	75	DRIVER	28.00	8.90	STEEL
Tmax=	350	FRAME	20.50	1.10	INVAR
Delta T=	275	SPECIMEN	8.50	1.20	PMC
		ENDPLATES	28	8.9	STEEL

1. CTE OF ENDPLATES AND MIDPLATE WERE NOT INCLUDED IN INDUCED STRAIN
   CAN ESTIMATE EFFECTS OF PRESENT FIXTURE BY ADDING END + MIDPLATE THICKNESSES TO DRIVER LENGTH

2. EFFECTIVE WIDTH FOR BEAM BENDING OF ENDPLATES ASSUMED TO BE 0.5 INCHES

3. ESTIMATED VOLUME ASSUMES: (1) 0.5 IN. BETWEEN DRIVER, RODS, SPECIMENS AND PLATE EDGES
   (2) .06 ADDED FOR FRAME THREADS, (3) MIDPLATE THICKNESS=0.5
4. CONSTRAINTS: VOLUME<500 IN.^3, LENGTH<24 IN., STRAIN>2500, MARGINS OF SAFETY>0.

Figure 4.1-6. Volume-Optimized Fixture No. 1

SUMMARY INFORMATION

THERMALLY-OPTIMIZED FIXTURE - #1

PERFORMANCE		GEOMETRY		STRESS / MARGINS	
FIXTURE MATL COST:	13.12	FIXTURE HEIGHT=	18.15	LOAD=	1904.00
FIXTURE VOLUME=	64.58	DRIVER HEIGHT=	14.15	DRIVER BUCKLING=	0.00
SPECIMEN STRAIN=	2500	SPECIMEN LENGTH=	4.00	SPECIMEN BUCKLING=	4.02
FIXTURE MASS=	2.54	ENDPLATE THKNS=	0.49	DRIVER YIELD (cys)=	1.79
FIX DIFFUSIVITY/VOL.	0.03	MIDPLATE THKNS=	0.50	FRAME YIELD (tys)=	0.00
ADJUSTABILITY	EASY			FRAME FATIGUE=	0.20
DRIFT	?	DRIVER DIAMETER=	0.54	DRIVER FATIGUE=	3.35
		FRAME ROD DIA.=	0.27		
		SPECIMEN THICKNESS=	0.179		
		SPECIMEN WIDTH=	0.50		
		BASEPLATE LENGTH=	1.87		
		BASEPLATE WIDTH=	1.54		

TEMPERATURE DATA		MATERIAL PROPERTIES			
			MODULUS (msi)	CTE(x 10-6)	MATL
Tmin=	75	DRIVER	28.00	8.90	STEEL
Tmax=	350	FRAME	20.50	1.10	INVAR
Delta T=	275	SPECIMEN	8.50	1.20	PMC
		ENDPLATES	28	8.9	STEEL

1. CTE OF ENDPLATES AND MIDPLATE WERE NOT INCLUDED IN INDUCED STRAIN
   CAN ESTIMATE EFFECTS OF PRESENT FIXTURE BY ADDING END + MIDPLATE THICKNESSES TO DRIVER LENGTH

2. EFFECTIVE WIDTH FOR BEAM BENDING OF ENDPLATES ASSUMED TO BE 0.5 INCHES

3. ESTIMATED VOLUME ASSUMES: (1) 0.5 IN. BETWEEN DRIVER, RODS, SPECIMENS AND PLATE EDGES
   (2) .06 ADDED FOR FRAME THREADS, (3) MIDPLATE THICKNESS=0.5
4. CONSTRAINTS: VOLUME<500 IN.^3, LENGTH<24 IN., STRAIN>2500, MARGINS OF SAFETY>0.

Figure 4.1-7. Thermally Optimized Fixture No. 1

SUMMARY INFORMATION

MAXIMUM STRAIN OPTIMIZED FIXTURE - #1

PERFORMANCE		GEOMETRY		STRESS / MARGINS	
FIXTURE MATL COST:	514.10	FIXTURE HEIGHT=	24.00	LOAD=	7281.16
FIXTURE VOLUME=	500.00	DRIVER HEIGHT=	20.00	DRIVER BUCKLING=	9.05
SPECIMEN STRAIN=	9560	SPECIMEN LENGTH=	4.00	SPECIMEN BUCKLING=	0.31
FIXTURE MASS=	70.50	ENDPLATE THKNS=	3.46	DRIVER YIELD (cys)=	5.40
FIX DIFFUSIVITY/VOL.	0.95	MIDPLATE THKNS=	0.50	FRAME YIELD (tys)=	9.87
ADJUSTABILITY	EASY			FRAME FATIGUE=	12.05
DRIFT	?	DRIVER DIAMETER=	1.60	DRIVER FATIGUE=	8.98
		FRAME ROD DIA.=	1.74		
		SPECIMEN THICKNESS=	0.179		
		SPECIMEN WIDTH=	0.50		
		BASEPLATE LENGTH=	4.39		
		BASEPLATE WIDTH=	2.74		

TEMPERATURE DATA		MATERIAL PROPERTIES			
			MODULUS (msi)	CTE(x 10-6)	MATL
Tmin=	75	DRIVER	28.00	8.90	STEEL
Tmax=	350	FRAME	20.50	1.10	INVAR
Delta T=	275	SPECIMEN	8.50	1.20	PMC
		ENDPLATES	28	8.9	STEEL

1. CTE OF ENDPLATES AND MIDPLATE WERE NOT INCLUDED IN INDUCED STRAIN
   CAN ESTIMATE EFFECTS OF PRESENT FIXTURE BY ADDING END + MIDPLATE THICKNESSES TO DRIVER LENGTH

2. EFFECTIVE WIDTH FOR BEAM BENDING OF ENDPLATES ASSUMED TO BE 0.5 INCHES

3. ESTIMATED VOLUME ASSUMES: (1) 0.5 IN. BETWEEN DRIVER, RODS, SPECIMENS AND PLATE EDGES
   (2) .06 ADDED FOR FRAME THREADS, (3) MIDPLATE THICKNESS=0.5
4. CONSTRAINTS: VOLUME<500 IN.^3, LENGTH<24 IN., STRAIN>2500, MARGINS OF SAFETY>0.

Figure 4.1-8. Maximum-Strain-Optimized Fixture No. 1

4.2 FIXTURE ANALYSIS

The fixture actuation concept is quite simple: because the stainless-steel driver has a much higher CTE than the invar reaction rods (9.0 microstrain/°F versus 1.1 microstrain/°F), as temperature increases, the driver expands and exerts a compressive force on the specimen, which is reacted by the relatively constant-length invar reaction rods. An estimate of the applied strain produced by the fixture as shown in figure 4.1-2 can be obtained by writing an equation for the change in length of each component (driver, reaction rods, and specimen) due to thermal expansion and relative stiffness. Beginning with the relations shown in equations 1, 2 and 3 below, an equation for the strain applied to the specimen, equation 4, can be derived (for simplicity, the reaction rods are treated as one rod with twice the cross-sectional area of an individual rod). The subscripts denote D = driver, R = reaction, and S = specimen.

$$P_S = P_D = -P_R \tag{1}$$

where P = load

$$\Delta L_R = \Delta L_S + \Delta L_D \tag{2}$$

where ΔL = total change in length

$$\varepsilon_S = \frac{P_S}{A_S E_S} \tag{3}$$

$$\varepsilon_S = \frac{\Delta T(C_S L_S - C_R L_R + C_D L_D)}{\left(L_S + L_R\left(\frac{E_S A_S}{E_R A_R}\right) + L_D\left(\frac{E_S A_S}{E_D A_D}\right)\right)} \tag{4}$$

where:

- ΔT = temperature change
- C = coefficient of thermal expansion
- L = original length
- A = cross-sectional area
- E = modulus

Note from equation 4 that the predicted specimen strain is dominated by the CTEs in the numerator, and by the ratio of specimen stiffness to the stiffness of the other components in the denominator. It is also important to note that the predictions based on this equation will be higher than the actual values, as no provision for flexing of the load platens is included. This feature is, however, included in the analysis spreadsheet developed for this task.

The expected specimen buckling strain shown can be estimated using Euler's equation:

$$\sigma_{critical} = \frac{\pi^2 E}{(L'/k)^2} \tag{5}$$

where:

$\sigma_{critical}$ = critical stress

L' = length/2 (correct for clamped end fixity)

k = $(I/A)^{1/2}$ (I = moment of inertia)

A program for analysis and optimization of DiCTE fixture designs was created for a variation of fixture design No. 1 (compression). Because the basic principle for obtaining strain in the specimen is similar in all strain-controlled fixtures, only minor modifications were required to apply this analysis tool to other DiCTE fixture designs. The program is written using an Excel spreadsheet and analyzes induced strain in the specimen (for any given temperature difference) and all pertinent failure modes of the fixture and specimen. For the compression fixture mentioned above, these failure modes, along with a brief description of the analysis method and the preliminary safety factor used for analysis, are listed in figure 4.2-1.

Failure Mode	Analysis Method	Safety Factor
Compression strength failure of specimen	Maximum strain	1.2
Compression buckling of specimen	• Wide column buckling • Plate buckling	1.1
Compression buckling of driver	Euler or Johnson-Euler	3.0
Compression yield of driver	Stress	3.0
Tensile yield of frame	Stress	3.0
Tensile ultimate of frame	Stress	3.0
Frame fatigue	Endurance limit	10% under limit

Figure 4.2-1. Safety Factors Used in Design

Note that this spreadsheet incorporated refinements of the aforementioned basic equations such as inclusion of endplate bending effects and corrections due to Poisson ratio effects in specimen buckling. Using one of two numerical optimization routines, the analyst is able to determine the lengths and cross-sectional areas required (for the driver and frame), which lead to the minimal fixture volume. This will quickly perform tasks such as determination of most efficient combinations of materials for the driver and frame and determination of the sensitivity of induced strain or fixture volume to the effects of variables such as frame modulus, specimen end fixity, or driver cross-sectional area.

Constraints used in the optimization analysis include (1) the minimum strain value required for a typical quasi-isotropic layup of an intermediate modulus specimen must be greater than 3,000 microstrain for cycling from room temperature to 250°F and (2) margins of safety (including appropriate safety factors) must be greater than zero. Material cost data were collected so that some capability could be developed for optimization based on material cost. Assuming similar amounts of machining and assembly requirements (within a given fixture type), this should give a rough estimate of relative cost of fixtures using differing material combinations.

4.3 FIXTURE DESIGNS

4.3.1 Compression Fixture Design

The downselected TAC fixture configuration is shown in figure 4.3.1-1. The fixture was initially configured as shown on the left, but after 61 cycles, a thermocouple failure coupled with fixture alignment problems and a miswired oven overtemp shutoff led to specimen failure. Subsequent analysis showed the configuration on the right was superior in providing even, symmetric loading to the specimen. The TAC fixture was modified to this configuration for the remainder of the testing. Figure 4.3.1-2 shows detail design parameters.

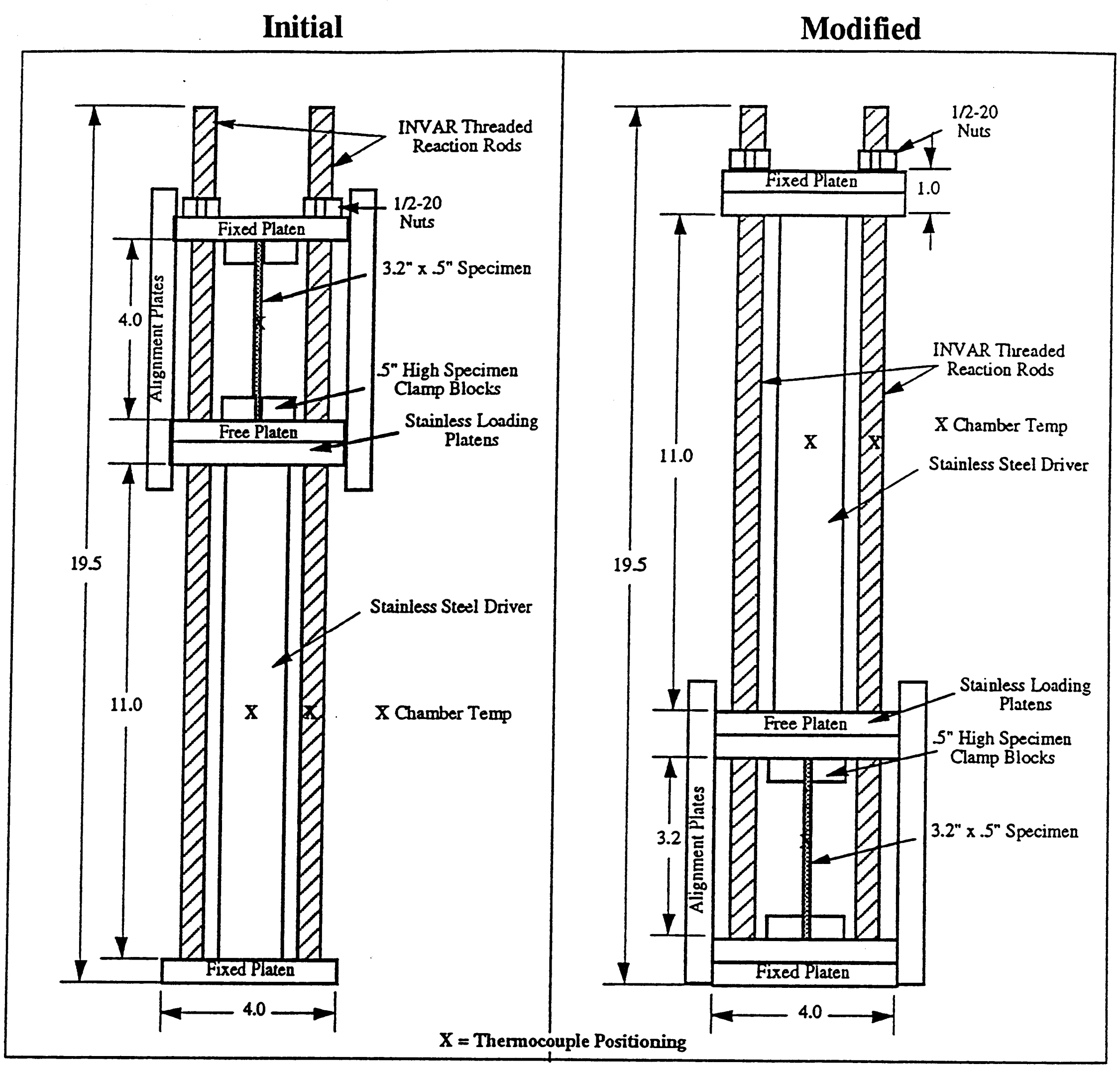


Figure 4.3.1-1. Initial and Modified Compression Fixture Schematic

Reaction (invar)		Driver (316 SS)		Specimen	
Length (in) =	16.7	Length (in) =	13.5	Length (in) =	3.2
Area 2 rods (in^2) =	0.341	Area (in^2) =	1.767	Area (in^2) =	0.093
Modulus (psi) =	20.5E+6	Modulus (psi) =	28.0E+6	Modulus (psi) =	8.5E+6
CTE (in/in) =	1.40E-06	CTE (in/in) =	8.90E-06	CTE (in/in) =	1.10E-06
1 rod dia (in)=	0.466	Diameter (in) =	1.500	Thickness (in) =	0.185
				Width (in) =	0.500

Figure 4.3.1-2. Compression Fixture and Specimen Analysis Parameters

4.3.2 Compression Fixture Strain Predictions

Based on the values shown in figure 4.3.1-2, a conservative estimate of the expected thermally induced strain for the prototype TAC fixture is shown by the solid line in figure 4.3.2-1. These values do not reflect endplate bending. (Boeing analyzed for endplate bending and predicted values within 1% of those observed during test.) A sensitivity study was conducted to determine the effect of specimen stiffness. The dashed line predicts strains for a specimen with 10% higher stiffness. The predicted strains do not vary significantly from the baseline. Also note that the predicted maximum strains are well below the buckling strain.

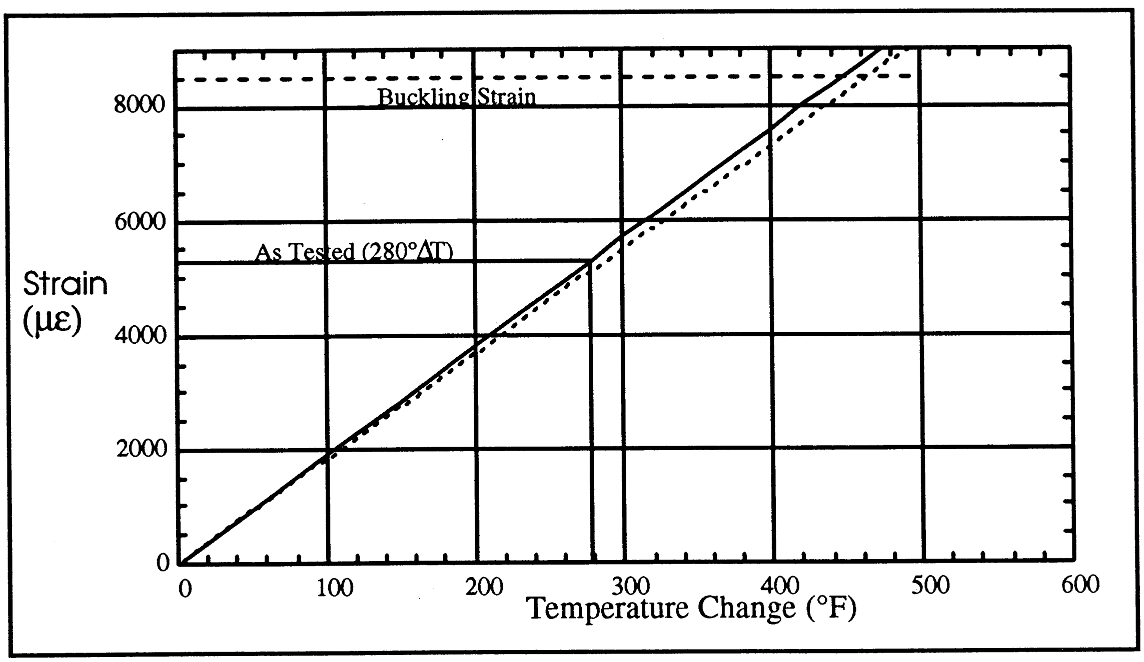


Figure 4.3.2-1. Predicted Compression Strain Versus Temperature Change

4.3.3 Tension Fixture Design

The TAT fixture design parameters included the desired specimen dimensions and material, thermal cycle maximum and minimum, and the desired applied strain. Figure 4.3.3-1 outlines these properties.

Spec Length (in)	Spec Width (in)	# Plies (quasi)	Min. Temp. (°F)	Max. Temp. (°F)	Target Strain (με)
10.0	1.0	8	70	350	4,000

Figure 4.3.3-1. Tension Fixture and Specimen Design Parameters

Load was to be applied in phase with a thermal cycle by using two materials with dissimilar CTEs. Stainless steel 304 and invar steel, with CTEs of 9.75 microstrain/°F versus 1.1 microstrain/°F, respectively, were chosen as the fixturing materials. Actuation is simple: a specimen placed in parallel with the two fixture materials could be forced to stretch an amount equal to the difference in expansion of the two steels, minus any expansion of the specimen (the CTE of which is comparable to invar) and any mechanical strain of the fixture components. Design of the fixture therefore took into account each component's CTE and stiffness.

The final design parameter, beyond the size and shape of the fixture, is the heat transfer of each component. The thermal cycle time necessary for the fixture to reach equilibrium is dependent on each component's ability to heat and cool rapidly. Optimization of the surface and cross-sectional areas of each component is therefore important in order to minimize necessary cycle times.

Consideration of the above issues, as well as size and ease of alignment of the specimen in the fixture, led to the configuration shown in figure 4.3.3-2. The stainless-steel tube was chosen because of its large surface area, which maximizes heat transfer and its inherent alignment and stability advantages. Optimization of the various parameters was accomplished using the Microsoft Excel Solver program. Specimen strain was calculated with the same program.

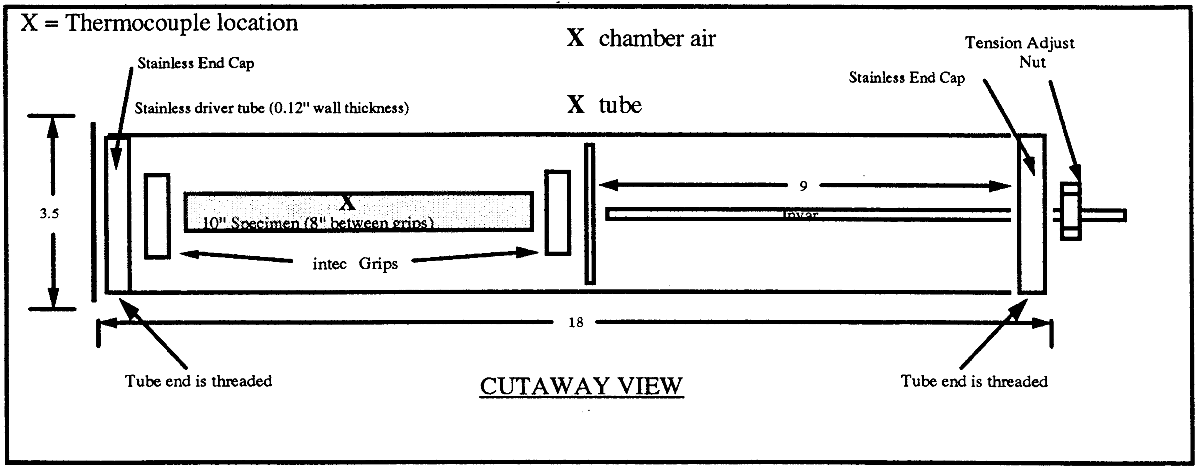


Figure 4.3.3-2. Tensile Fixture Schematic

Figure 4.3.3-3 shows detail design and analysis parameters, along with the predicted specimen strain at the maximum test temperature.

Tube Parameters		**Invar Parameters**		**Specimen Parameters**	
Length (in) =	17.0	Length (in) =	9.0	Length (in) =	8.0
Outside Dia (in)=	3.50	Diameter (in) =	0.63	Thickness (in) =	0.047
Wall Thkns (in)=	0.12	Area (in^2) =	0.307	Width (in) =	1.000
Area (in^2) =	0.850	Modulus (Msi) =	20.50	Area (in^2) =	0.0448
Modulus (Msi) =	28.00	CTE (µin/in/°F) =	1.10	Modulus (Msi) =	8.50
CTE (µin/in/°F) =	9.75			CTE (µin/in/°F) =	1.20
Temp. Variation		**SPECIMEN CONDITIONS**			
Delta T (°F) =	280	Strain (µin/in)=	4626		
		Load (lbs)=	1839		

Figure 4.3.3-3. Tension Fixture and Specimen Analysis Parameters

4.3.4 Tension Fixture Strain Predictions

Using the values of figure 4.3.3-3 for the variables shown, a curve of expected applied strain versus change in temperature can be drawn, as shown in figure 4.3.4-1. For the tension case, an increase in specimen stiffness of 10% provided a change in applied strain of only about 1%, because of the much higher stiffness of the invar and stainless-steel tube. It is important to note that the simple expression given in section 4.2 does not include terms for flexure or thermal expansion of the end caps. For this reason, the spreadsheet was modified to include endplate bending and thermal expansion. The tool then predicted strains within 0.6% of those recorded in test.

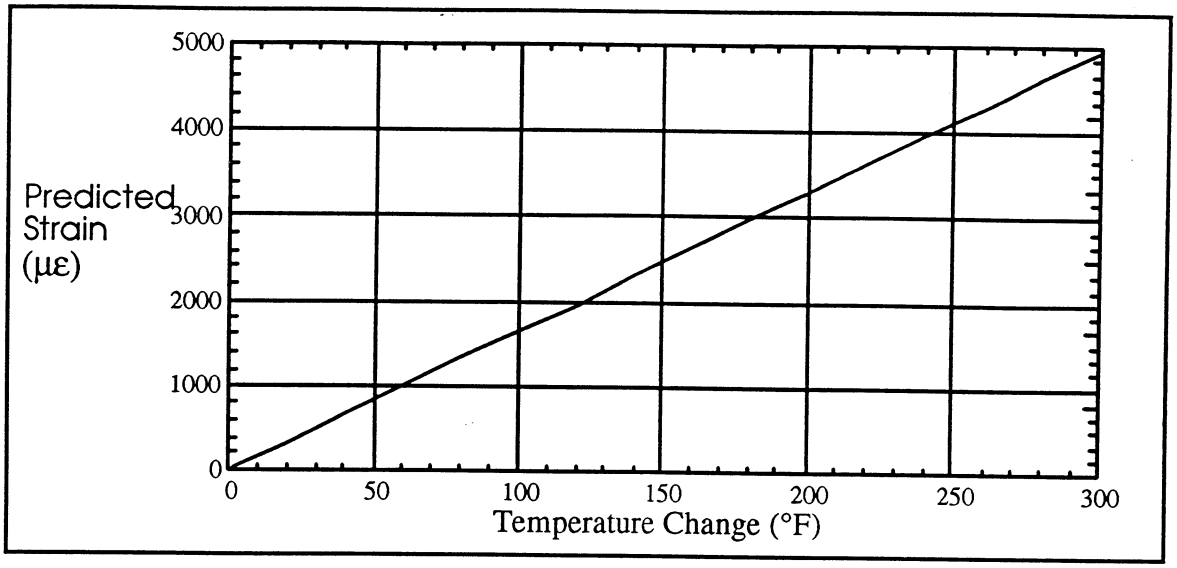


Figure 4.3.4-1. Predicted Tensile Strain Versus Temperature Change

4.4 FIXTURE VALIDATION TESTING

4.4.1 Compression Fixture

4.4.1.1 Test Specimens and Instrumentation

Four 0.5- by 4- by 0.1792-in (32-ply) intermediate modulus bismaleimide (BMI) specimens were machined by Intec from a Boeing-furnished laminate. (The BMI laminate cure cycle is contained in appendix A.) Two of these specimens were strain-gaged as shown in figure 4.4.1-1, and the remaining two were held as spares. The specimen geometry was chosen to match the end-loaded compression specimen defined in the SACMA SRM1-88 specification (similar to the ASTM D695 geometry without tabs).

Strain gages were Measurements Group model WK-00-125BB-350, a single-axis, 350Ω gage with a 0.125-in gage length. The WK-00 series gages are self-temperature-compensating to correct for thermal drift and are matched to the approximate CTE of graphite-reinforced PMCs. The gages were applied with M-Bond 610, a high-temperature strain gage adhesive, cured for 1 hr in 350°F dry heat.

Temperature compensation error for these gages is rated at less than +40 microstrain and -145 microstrain (ref. 5) and was further reduced as described below. The second strain-gaged specimen, termed the "control specimen," was suspended in the thermal environment, and one gage was monitored to track thermally induced axial strains. The loaded specimen strains could then be corrected for thermal expansion of the specimen and strain gage thermal responses by subtracting the control strain from the loaded specimen strains. These corrected strains were termed "induced strains." In this way, strain errors were controlled to well below the rated values.

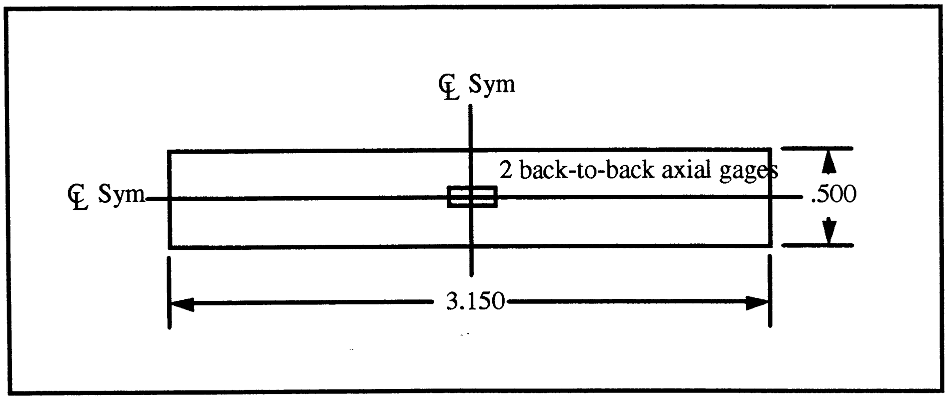


Figure 4.4.1-1. Strain Gage Schematic

Calibrated type K thermocouples were used to monitor the temperature of the system, one each on the specimen, the driver, reaction rod, and in the chamber air near the specimen. Two additional thermocouples were used to supply control and overtemperature feedback to Watlow model 942 and 985 PID (proportional integral derivative) controllers, respectively. These sensors were located with the chamber-monitoring thermocouple, so feedback control was supplied by the chamber air temperature.

The thermocouples that monitored surface temperature were adhered with high-temperature fiberglass tape, which kept the thermocouples in contact with the surface throughout the test. The outer portions of the sensors were insulated to minimize the influence of air temperature.

Data from the strain gages and thermocouples were acquired using OnGuard 1.0, a Microsoft Windows-based data acquisition system produced by Intec. Strain and temperature data were collected at 5-min intervals throughout the duration of the test. Data from the two process feedback thermocouples discussed above were not recorded.

4.4.1.2 Test Procedure

The specimen was mounted in the fixture by placing it between the 0.5-in clamping blocks on the lower platen (fig. 4.3.1-1), verifying vertical placement with a precision square, and securing the blocks with 0.25-in bolts. The specimen was then clamped in the upper platen, using steel alignment plates to ensure alignment with the lower platen. The platen assembly was then placed in the fixture and tightened into place with the 0.5-in nuts. Symmetric front-to-back loading was assessed by activating the data acquisition system and evenly tightening the nuts. When the initial configuration was used, it was found that tightening the nuts caused significant torsion of the two reaction rods, which contributed to uneven front-to-back loading of the specimen by up to 30% at maximum temperature. In contrast, the modified configuration gave front-to-back agreement within 6% throughout the thermal cycle.

Once alignment was optimized (this was front-to-back agreement within 15% at 3,000 microstrain in the initial configuration and within 2% at 3,000 microstrain for the modified version), a preload of about 300 microstrain was applied, the strain gages and timer were initialized, and thermal cycling was started.

The thermal chamber used was a Bemco model FTU-3.2-100/600, equipped with the process and overtemperature controllers listed above. The control unit was programmed to automatically maintain the appropriate ramp and soak times using electric elements for heating and liquid nitrogen injection for cooling. The overtemperature controller sensitivity was 20°F over the target temperature.

4.4.1.3 Thermal/Mechanical Testing

The thermal cycle profile used for testing is shown in figure 4.4.1-2.

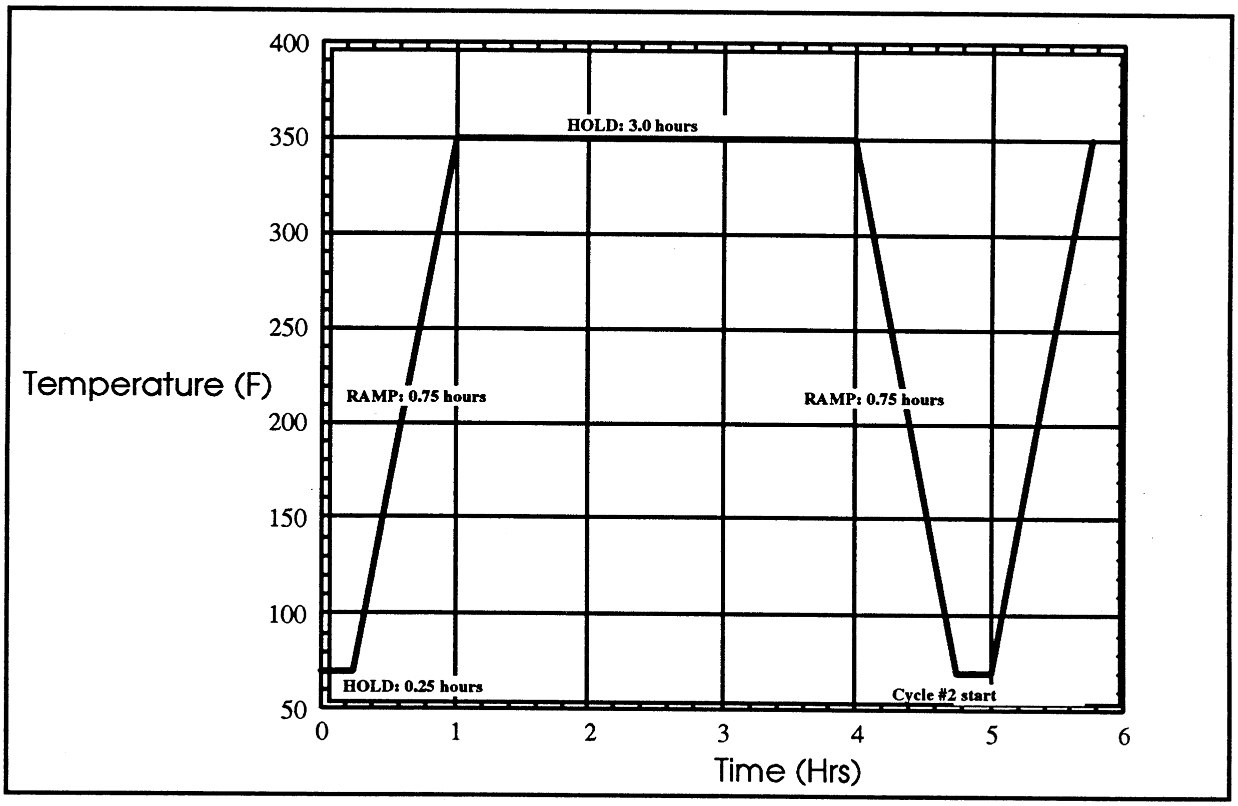


Figure 4.4.1-2. Thermal Cycle Profile

This thermal cycle contains a 3-hr soak time at 350°F, which is near the upper limit of an actual HSCT ground-air-ground cycle. Time was required to reach maximum strain because of the substantial thermal mass in the driver. One complete cycle is of 4.75-hr duration. For accelerated testing, thermal optimization of the fixture is possible, which would significantly reduce the time at temperature necessary to achieve maximum strain.

It is interesting to note that design of the relative heat transfer capabilities of the reaction rods and driver is theoretically possible, which would drive strain spikes at the end of each high-temperature hold. For example; if a material with a higher CTE than invar, but still less than the driver, were used for the reaction rods and the heat transfer of the driver was significantly higher than the reaction rods, the sudden temperature change at the end of the 350°F hold period would cause the reaction rods to cool (and shrink) much faster than the driver. This would thereby spike the compressive strain until the driver cooled enough to negate the spike. An example curve is shown in figure 4.4.1-3.

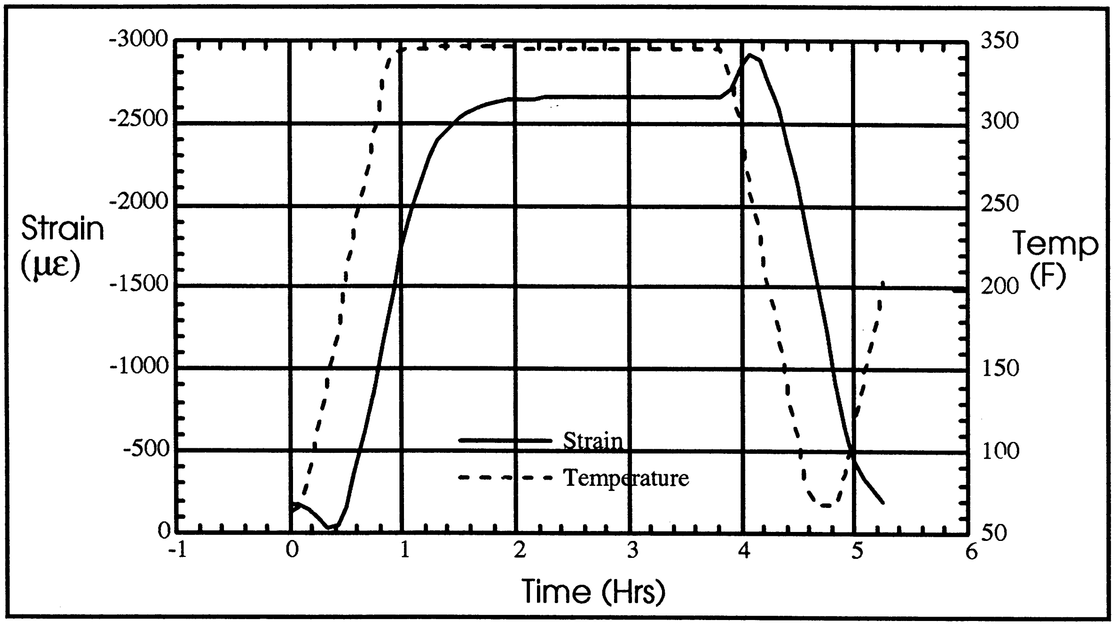


Figure 4.4.1-3. Theoretical Strain Spike

As mentioned previously, the first 100-cycle test performed with the initial configuration shown in figure 4.3.1-1 ended prematurely at cycle 61 when an overtemperature condition and specimen misalignment caused specimen failure. The overtemperature condition was caused by the gradual abrasion of the insulation surrounding the controlling thermocouple by a sharp metal burr in the chamber wall. When the thermocouple wires were eventually exposed and shorted across the burr, a low-temperature feedback signal was sent to the controller. The heating elements were thereby activated, but the low feedback signal was unaffected. In this way, the temperature was driven to 445°F and the asymmetric loading of the specimen due to the fixture torsion discussed above promoted severe buckling and eventual failure. Normally, the overtemperature protection controller would have shut down the system at 370°F, but it was inactive because of a programming error. The specimen strain and temperature data for cycle 61 are shown in figure 4.4.1-4.

It can be seen in figure 4.3.2-1 that the analytical buckling strain of the specimen, assuming fixed end supports, is about 8,500 microstrain, which is applied at about 450°F. Although this is very near the point of dramatic buckling shown in figure 4.4.1-4, where the bag side strain inverted and became less compressive (at about 430°F) and the tool side became dramatically more compressive, buckling onset appears to begin at approximately 350°F. This trend was also seen in all cycles prior to cycle 61. The onset of buckling so far below the predicted buckling load (assuming fixed supports) demonstrates the less-than-clamped end fixity condition provided by the end-load grips, as well as off-axis loads due to fixture misalignment.

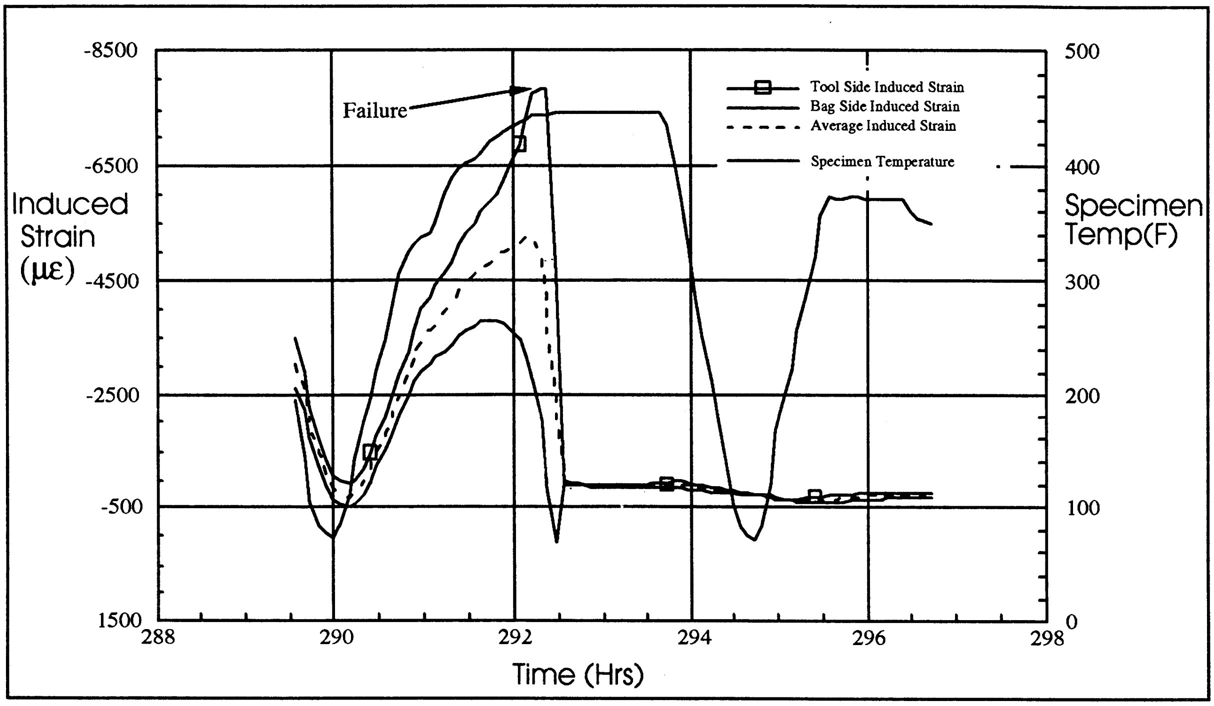


Figure 4.4.1-4. Trial No. 1, Buckling and Failure Event

After the specimen failed, Intec determined that reconfiguration of the assembly could significantly improve loading symmetry by minimizing the transfer of torque from the reaction rods to the specimen and maximizing the bending stiffness of the assembly in the vicinity of the specimen. After several additional single-cycle trials, the test program was restarted and successfully completed 100 cycles using the modified configuration shown in figure 4.3.1-1. No evidence of buckling was noted in the second trial.

The average temperature and induced strain history for trial No. 2 is shown in figure 4.4.1-5.

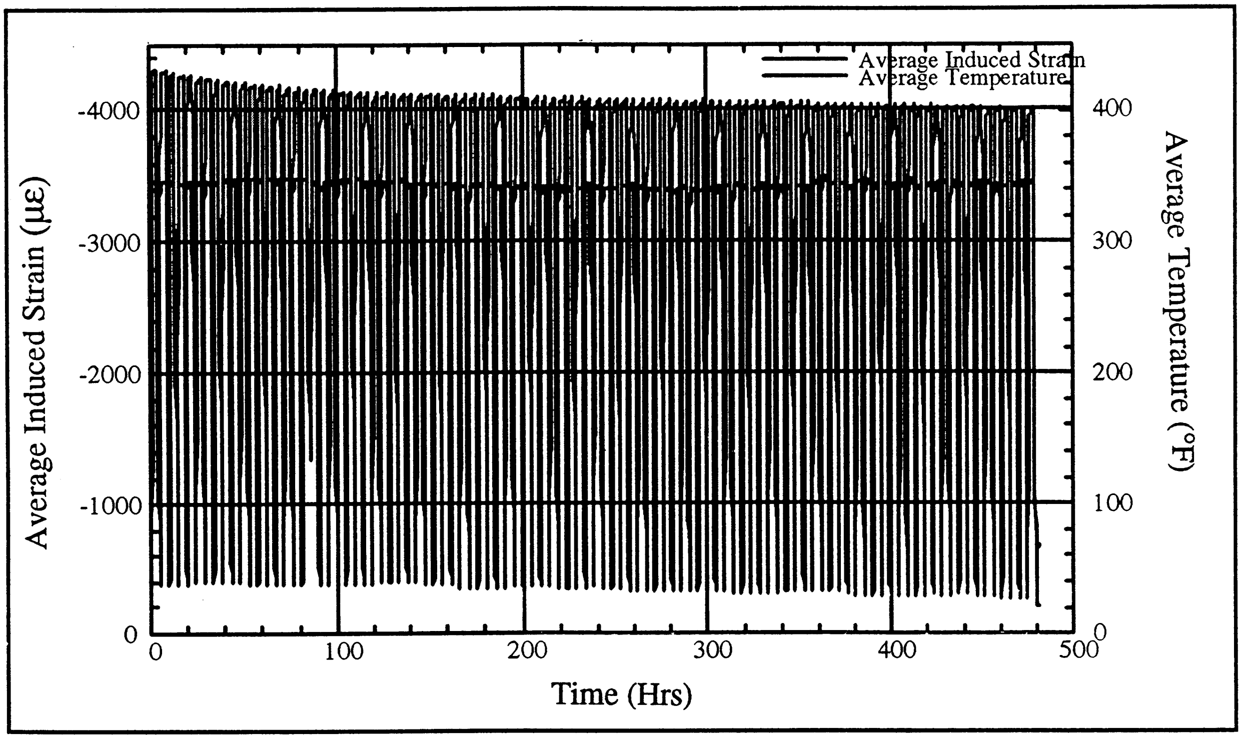


Figure 4.4.1-5. Trial No. 2, Average Temperature and Strain History

The short cycle at hour 85 (cycle 19) is not due to actual temperature cycle error, but to 13 missing data points caused by necessary data acquisition system maintenance. Cycle 19's shape before and after the missing hour is consistent with the previous and following cycles, indicating uninterrupted thermal cycling performance and relatively unchanged strain data.

The maximum and minimum average strains for each cycle shown in figure 4.4.1-5 demonstrate a generally decreasing trend with time. In order to characterize this effect as a result of specimen creep, fixture relaxation, and/or fixture seating or as an effect of averaging, the measured strains are shown for selected ranges in figure 4.4.1-6. Notice that the maximum induced tool strain is initially 250 microstrain higher than the induced bag strain, but by the 12th cycle, has stabilized to 100 microstrain below the bag strain, where it remains for the duration of the test. It appears that during the first 12 cycles, the specimen and fixture configuration is seating itself. This trend is typical of end-loaded specimen geometries and can be illustrated by plotting the difference between the two strains at the maximum of each cycle as a percentage of the maximum strain, as shown in figure 4.4.1-7. After cycle 12 (hour 55), the percentage difference remains consistently around 2.5%, indicating constant relative strains.

Also from figure 4.4.1-7, the low percentage difference indicates no propensity toward buckling, as opposed to the first trial in which the bag-to-tool difference at maximum strain was consistently over 25%.

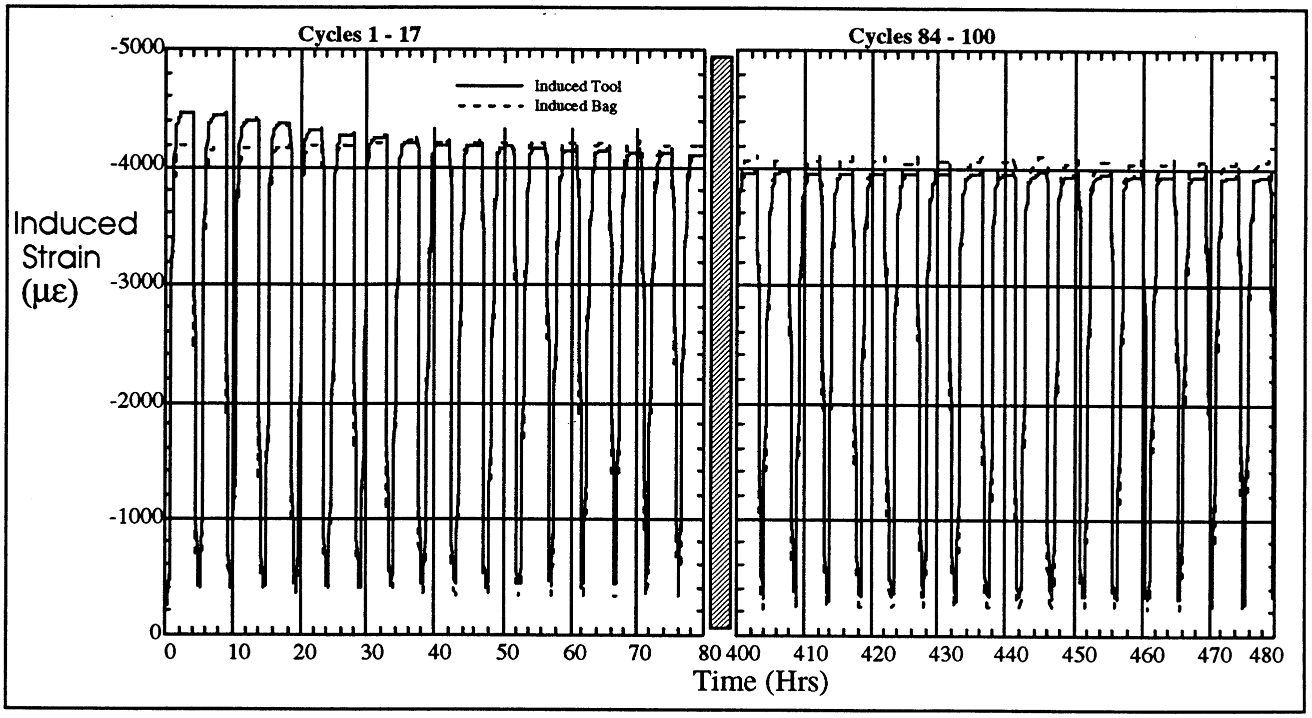


Figure 4.4.1-6. Strain Data Selected Cycles

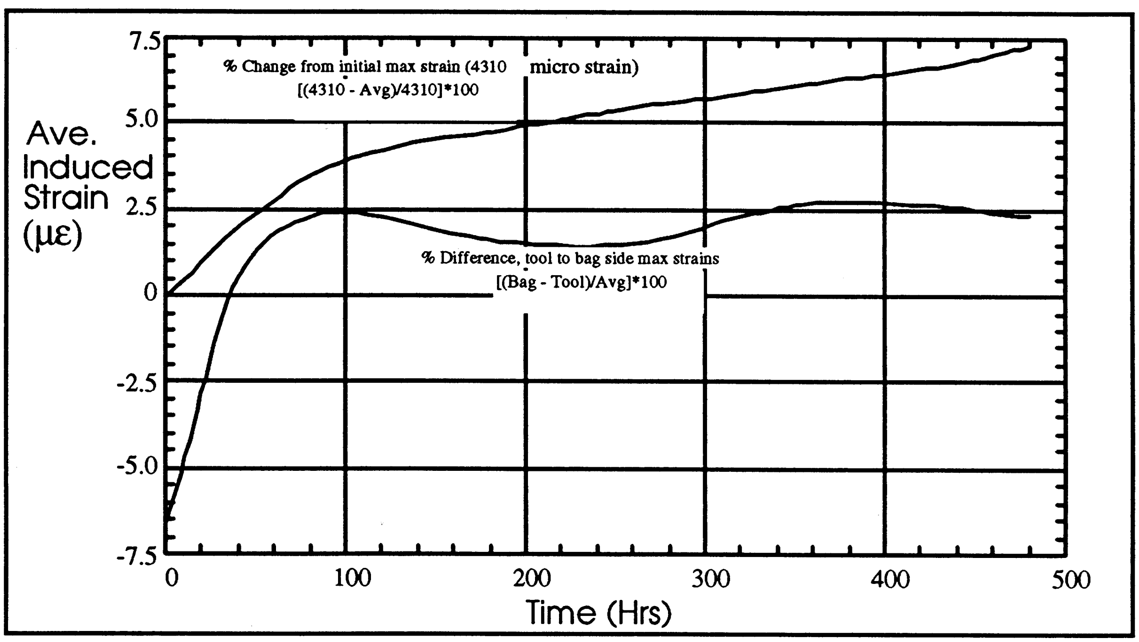


Figure 4.4.1-7. Changes in Maximum Strain as a Function of Time

4.4.1.4 Strain Loss Analysis

Because the bag and tool strains had reached relative equilibrium by the 12th cycle and did not change significantly after that point, it seems that fixture loading configuration is stable beyond at most the 20th cycle (95 hr). In fact, if the percentage difference between the maximum strain of each cycle and the initial average maximum strain is plotted as above in figure 4.4.1-7, the slope of the line is constant after cycle 20. Figure 4.4.1-8 shows the slopes of the linear curve fits of the maximum and minimum average strains for cycles 20 to 100. (Averages may be used because the maximum and minimum strain differences of the tool and bag strain gages are constant.) The decreasing maximum and minimum strains that are evident after cycle 20 are then due to either specimen creep and/or fixture relaxation. Further analysis indicates that fixture relaxation is probably the dominant phenomenon, although specimen creep is also occurring.

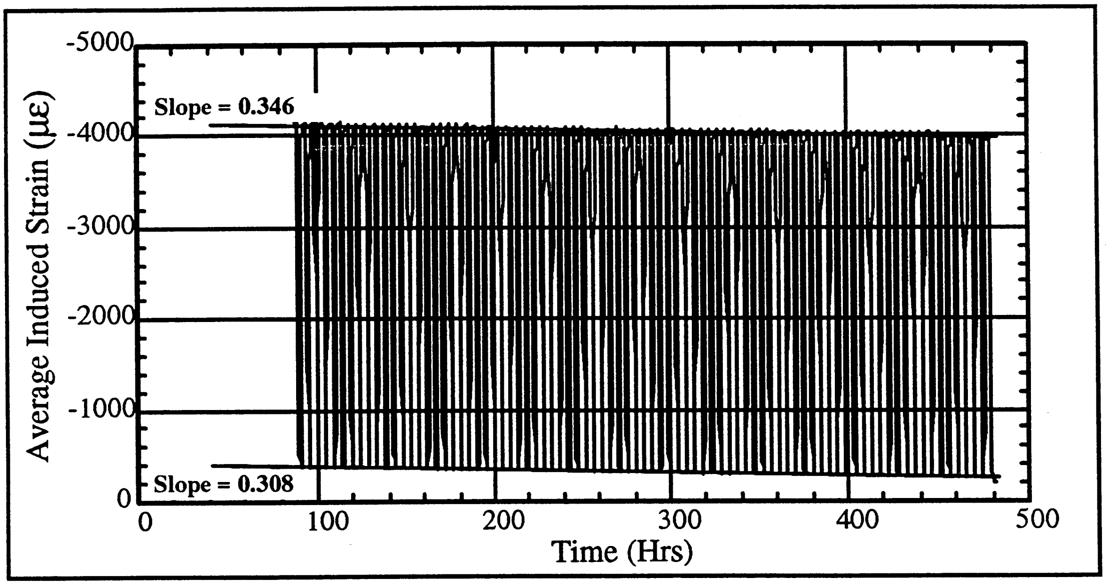


Figure 4.4.1-8. Maximum and Minimum Strain Trends

Fixture relaxation should result in equivalent maximum and minimum strain slopes greater than zero. As the fixture loosens by relaxation of the nuts, deformation, or other causes, the gap between loading platens increases, resulting in a lower applied strain throughout the loading cycle. Although both slopes shown in figure 4.4.1-8 are positive, the minimum strain slope is about 10% lower than the maximum strain slope. Although the standard deviation of each slope can vary up to several percent depending on which points are included in the curve fit, it seems probable that the difference between maximum and minimum strains **is** due to specimen creep. (The slope values as shown include all points from the beginning to the end of the maximum strain plateau (about 36 data points) for maximums, and the minimum three to five points for the minimums. Because data were collected every 5 min, this was deemed a more representative method of slope calculation than using only the maximum and minimum point of each cycle.)

Specimen creep is defined as the time-dependent portion of the deformation of a material under load. In this case, as the specimen crept, the strain gage would measure an increasing (more negative) *minimum* (unloaded) strain from cycle to cycle, but the maximum measured strain would remain unchanged because the fixture is displacement controlled. In this way, if no other phenomena were affecting the strains, one would expect a negative minimum strain slope and a maximum strain slope of zero. Therefore, if the effects of fixture relaxation and specimen creep were combined, the relative maximum and minimum slopes shown in figure 4.4.1-8 are reasonable and expected. The slopes measured in figure 4.4.1-8. correlate to a specimen creep rate and fixture relaxation rate of approximately 0.2 microstrain per cycle and 2.0 microstrain per cycle, respectively (after the first 20 cycles).

4.4.1.5 Discussion of Results

With several minor modifications, the current compression fixture design was found capable of performing its intended function; however, redesign of the fixture would significantly improve its performance (see sec. 4.5).

4.4.2 Tension Fixture

Testing consisted of several single-cycle checkout runs followed by fifty 4-hr cycles from room temperature to 350°F, simulating a simplified ground-air-ground temperature and load profile for the HSCT. This multiple-cycle testing of the prototype fixture was used to assess effects of fixture drift and specimen creep and determine probable calibration intervals for this fixture design. Thermal and mechanical strains and specimen and steel driver temperatures were monitored during the entire test.

4.4.2.1 Test Specimens and Instrumentation

Two quasi-laminate, eight-ply graphite specimens of an IM7/K3B material system were strain gaged as shown in figure 4.4.2-1. (The K3B Laminate cure cycle is contained in appendix A.) Specimen BC113-1 was loaded during an initial checkout cycle of 3-hr duration, and specimen BC113-4 was loaded during the 50-cycle test run. The axial gages on the unloaded control specimen were used to track thermally induced strains in both the preliminary and 50-cycle runs.

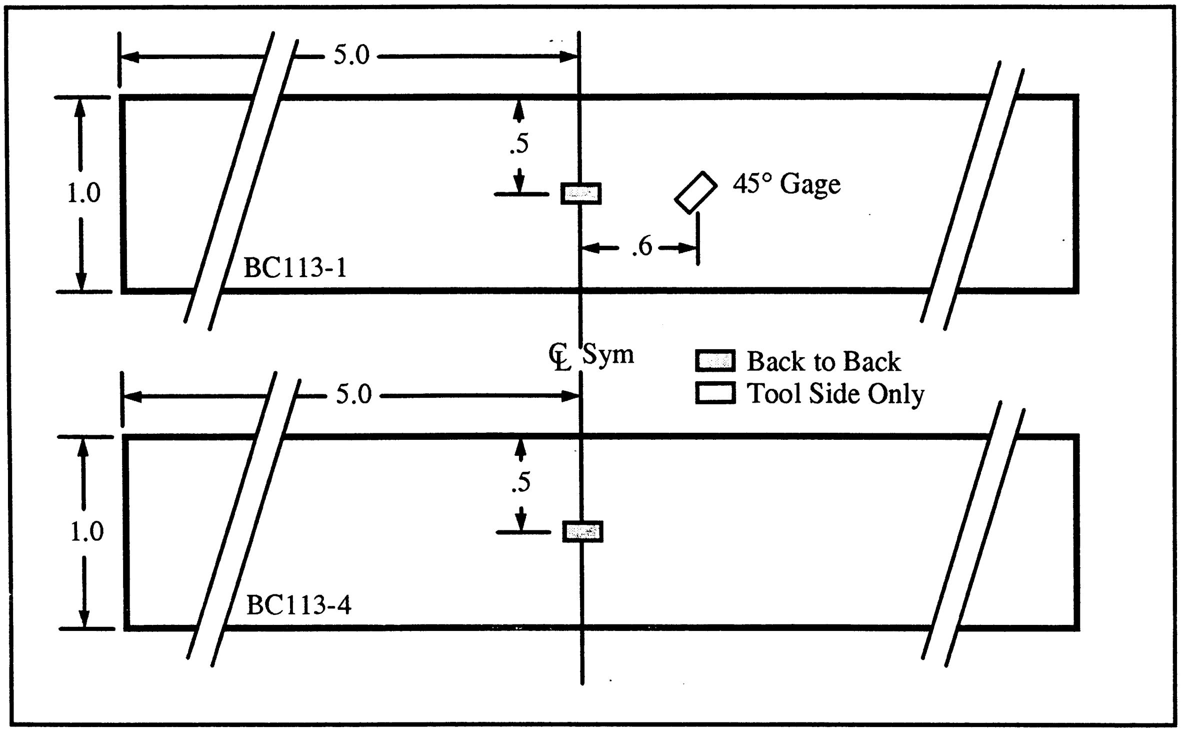


Figure 4.4.2-1. Strain Gage Schematic

Strain gages, thermocouples, chamber controllers, and data acquisition equipment and procedures were the same as those reported in section 4.4.1.

4.4.2.2 Test Procedure

The mechanical grips used in this program are designed for tensile or compressive loading over long time periods. A simple schematic of the grip assembly is shown in figure 4.4.2-2. Detail drawings of the grips are contained in the appendix B. The gripping surface of each wedge was textured by a chemical bonding process, producing a 100-grit surface. This surface allows nonslip gripping of graphite-reinforced PMCs without excessive damage to the outer plies of the material and may be easily varied from 350- to 30-grit for various material types. The grip assembly also allows specimen thickness to vary up to 0.25 in with only minor modifications.

Mounting the specimen in the mechanical grips provides for relatively easy specimen alignment, and the symmetric design of the fixture maintained alignment throughout the test. In fact, the tension fixture was far superior in ease of setup, alignment, and maintainability than the compression fixture.

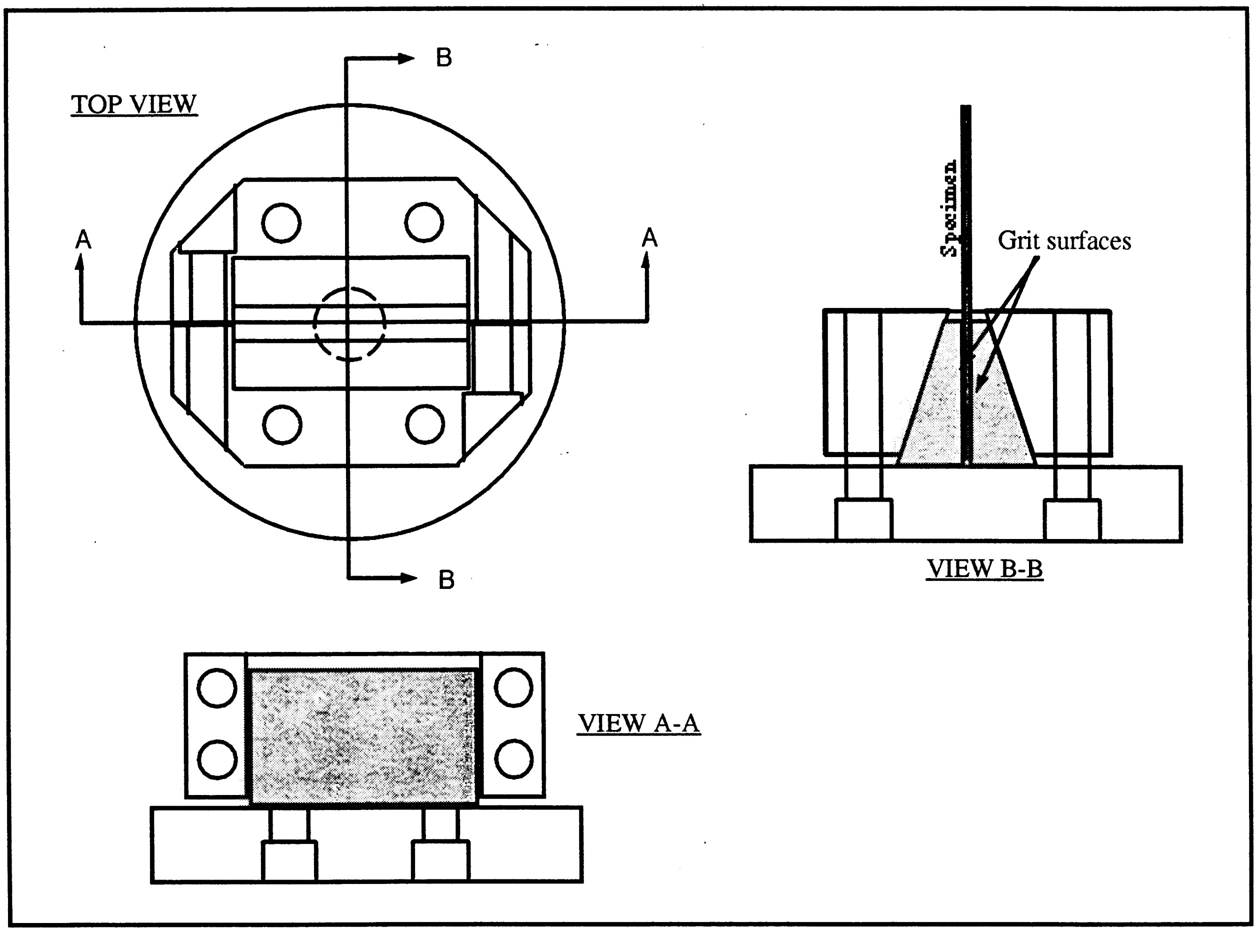


Figure 4.4.2-2. Mechanical Grips

Once the specimen was mounted in the grips, the invar rod was screwed into the middle grip plate and secured with a locknut. The specimen and invar assembly was then inserted into the tube and the end grip plate was screwed into the tube. The other end cap was then screwed into place, aligning keyways that were cut into the invar rod and the end cap and inserting a key. The key locked the invar rod into place, insulating the specimen from any torque applied by tightening the tension adjust nut. (See figure 4.3.1-1 for fixture assembly clarification.)

After the fixture was assembled, the data acquisition system was activated and the tension adjust nut was tightened to apply tension to the specimen. The back-to-back axial strain gages were monitored to verify symmetric front-to-back loading. If the gages indicated strains within 5% of each other, the system was considered aligned and ready for testing. The tension adjust nut was then positioned to supply approximately 150 microstrain to the specimen. The assembly was then placed in the thermal cycling chamber described in section 8.1.

As was done with the compression fixture checkout, two specimens were manufactured and strain gaged. The extra control specimen was suspended in the thermal environment and axial strains were monitored to track thermally induced axial strains. The loaded specimen strains could then be corrected for thermal expansion of the specimen and strain gage thermal responses by subtracting the control strain from the loaded specimen strains. These corrected strains were termed "induced strains." Note that only one axial control strain was monitored in the preliminary thermal cycle, but both a tool- and bag-side control strain were monitored during the extended 50-cycle test run. The 50-cycle test produced tool- and bag-side-induced strains by subtracting the tool and bag control strains from the corresponding loaded strains.

4.4.2.3 Thermal/Mechanical Testing

A preliminary single-cycle test was run with specimen BC113-1 in the fixture. This cycle was conducted to verify the strain and alignment performance of the fixture and provide an indication of the heat transfer capabilities of the fixture in preparation for defining the thermal cycle profile to be used for a 50-cycle test run. The trial thermal cycle used a 45-min ramp from 70°F to 350°F, followed by a 2.5-hr soak at 350°F and 45-min rampdown back to 70°F.

The strain and temperature data collected during the cycle are shown in figure 4.4.2-3. Based on the data, it is apparent that all components of the fixture assembly, including the tube and the specimen, reached equilibrium within less than 1 hr from the beginning of the soak.

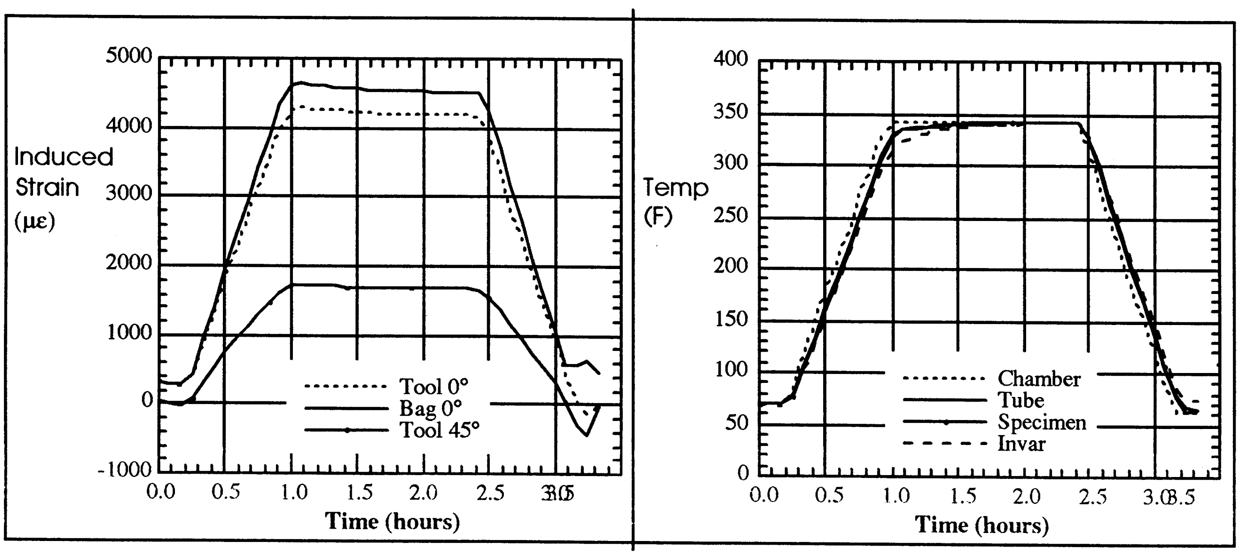


Figure 4.4.2-3. Preliminary Cycle Strain and Temperature Data

The tube design of this fixture allowed temperature equalization well over twice as fast as a similar compression fixture that used a solid steel driver. Note that the slowest heat transfer component of the fixture is the invar rod. Because this rod was also the component with the lowest CTE, its impact on specimen strain was slight, and the specimen relaxed only slightly after the invar reached equilibrium.

The temperatures shown in figure 4.4.2-3 plateau 4° to 5°F below the target temperature of 350°F. Because the control thermocouple (which was not monitored with the others) was located in close proximity to the chamber thermocouple, the difference is probably due to the insulation of the controlling sensor.

Several design parameters were verified by the single-cycle data. The test indicated that the predictions made in section 4.4 were very accurate (within 0.6%) and that the target tensile strains of 4,000 microstrain were met. Figure 4.4.2-4 shows the predicted and actual axial strains throughout the thermal cycle.

The preliminary cycle also showed reasonable agreement between the back-to-back axial strain gages (better than 8% throughout the cycle), indicating reasonable alignment of the fixturing. The specimen grips performed well with no evidence of specimen slippage under load. It was also apparent that a 2-hr soak at 350°F would be adequate to ensure that thermal equilibrium was reached.

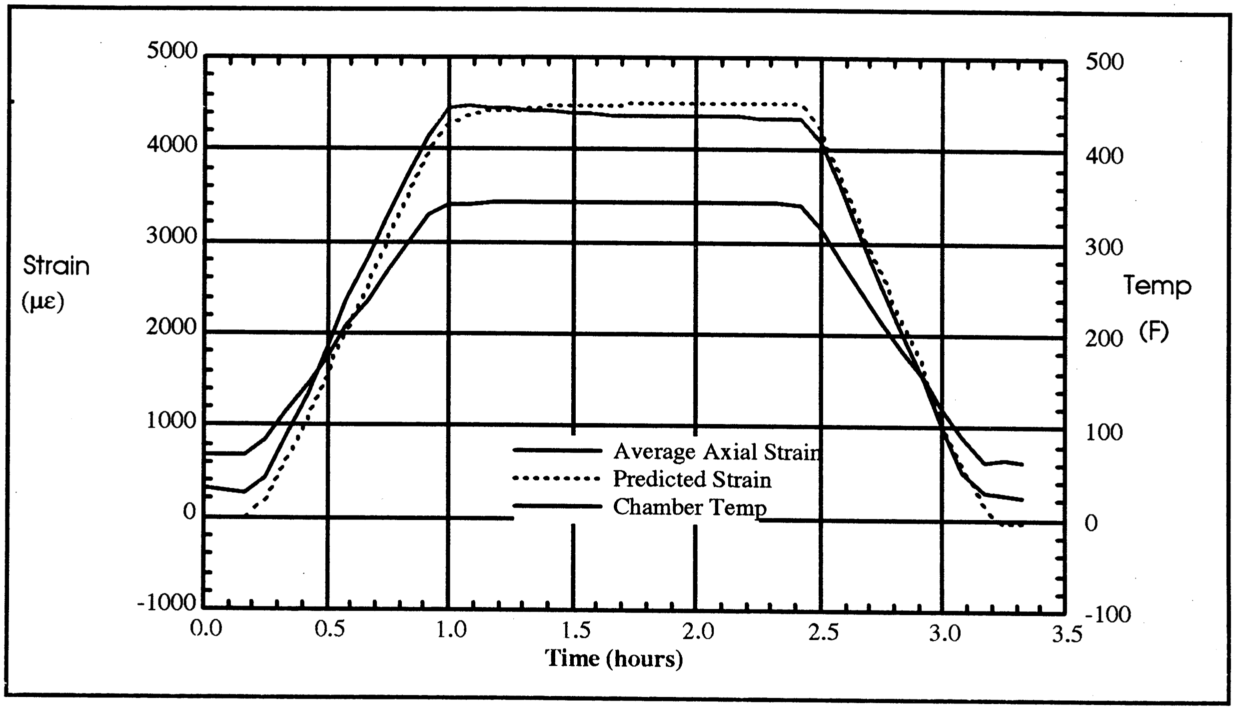


Figure 4.4.2-4. Predicted and Actual Strain Versus Time

At completion of the preliminary cycle, because little fixture or specimen refinement was necessary, a 50-cycle extended checkout test was started. The thermal cycle used for the extended test was identical to that described for the preliminary cycle, except the high-temperature soak time was shortened to 2.0 hr (from 2.5). The average temperature and induced strain history for all cycles is shown in figure 4.4.2-5. The four cycles between 75 and 86 hr were affected by a faulty liquid nitrogen (LN2) valve, which did not supply sufficient liquid nitrogen to completely cool the system within the required cycle time. The portion of the cycles above 200°F was not affected. Careful inspection of this figure also reveals that a total of 51 cycles were completed.

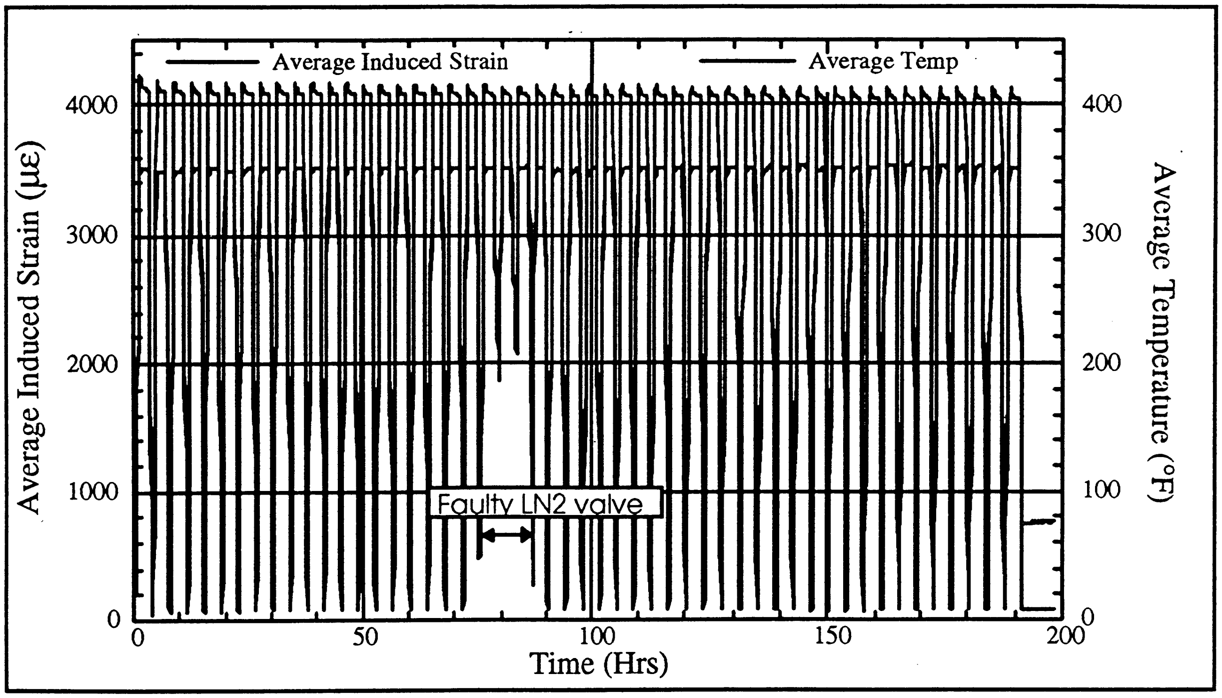


Figure 4.4.2-5. 50-Cycle Strain and Temperature Data

Three cycles representative of typical induced strains are plotted in figure 4.4.2-6 to illustrate the performance of each axial strain gage. As discussed above, induced strains were calculated by subtracting the thermal strains measured by the axial strain gages placed on specimen BC113-1 (which was in the test environment, but not loaded) from the mechanical and thermal strains measured by specimen BC113-4, which was in the test fixture. In this way, the strain errors induced by thermal expansion of the specimen relative to the strain gage, as well as by temperature changes in the gage leadwires, were minimized.

This figure demonstrates that the gages maintain an error of less than 5% through the cycle until the temperature was below approximately 85°F, at which point the strains diverge as the specimen buckled slightly. Apparently, the tube was at a temperature slightly above 70°F when the tensile preload was applied to the specimen at the beginning of the test. For the applied preload of 150 microstrain, a temperature delta of only about 10°F would be capable of driving the specimen into compression. In fact, when cycling was complete and the fixture was removed from the thermal chamber, the tension adjust nut was barely finger tight. Furthermore, no evidence of specimen slippage or fixture relaxation was present.

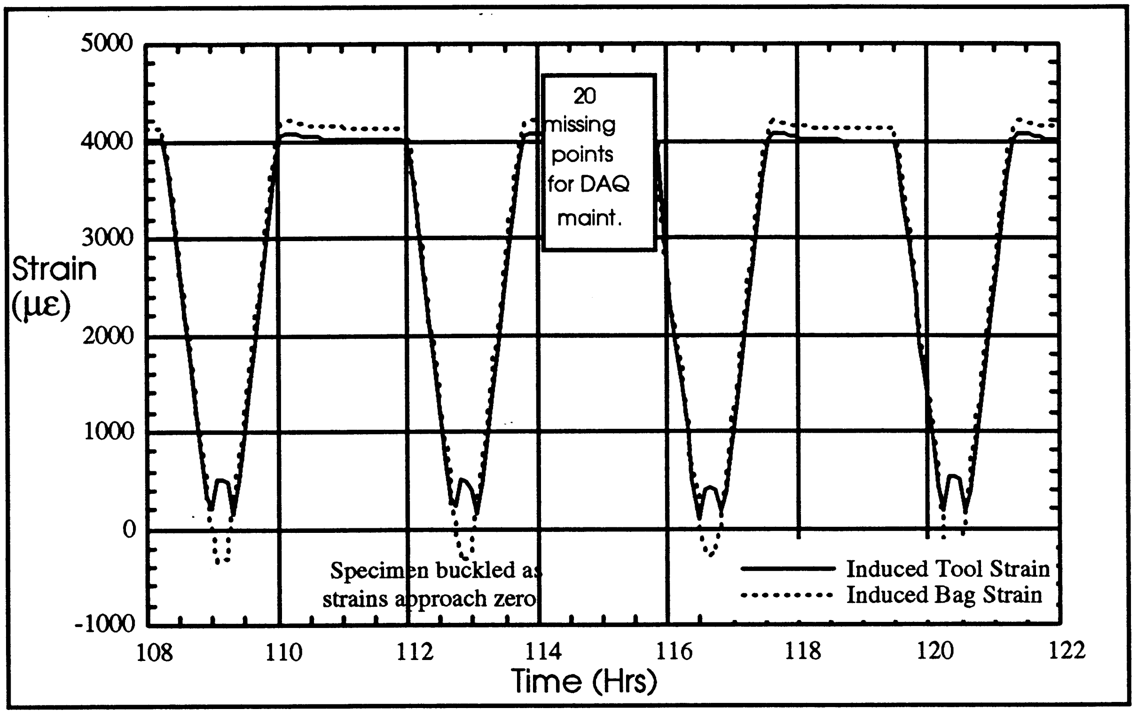


Figure 4.4.2-6. Representative Induced Strain Cycles

A total of 20 data points (1.5 hr) are missing from between hour 114 and hour 116, due to necessary maintenance of the data acquisition (DAQ) system. No apparent deviation from expected strain or temperature cycles was noted during this time.

Figure 4.4.2-7 shows the temperature data for a representative cycle from the three temperature channels monitored during the test: specimen, tube, and chamber. The invar rod was not monitored because its temperature was shown in the preliminary cycle to have minimal influence on the applied strains because of its relatively low CTE. The temperature sensors track each other extremely well, indicating good heat transfer properties of the tube and efficient heat transference to the specimen through the tube. The controlling thermocouple was also replaced and all cycles reached and settled at the target of 350°F. The cycle shown in figure 4.4.2-7 is virtually identical to all the temperature data for the other cycles (except those affected by the faulty LN2 valve discussed above).

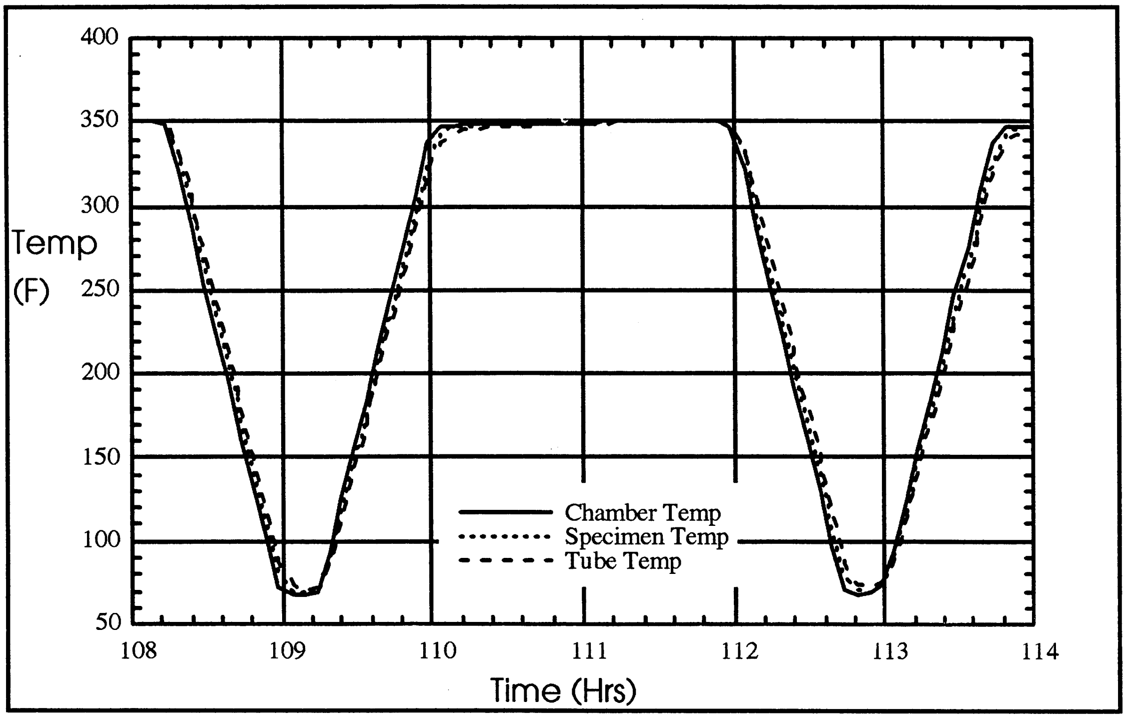


Figure 4.4.2-7. Typical Temperature Data

4.4.2.4 Strain Loss Analysis

Figure 4.4.2-5 showed an overview of the strains for the entire trial. Figure 4.4.2-8 shows details of first and last cycles. These figures show that the strains applied to the specimen are very consistent from the 1st to the 51st cycle. In contrast to the compression case, there is little evidence of either specimen creep or fixture relaxation. It is not surprising that little specimen creep should have taken place, because tension stiffness is much more fiber dominated than the compression case, the specimen was gripped (therefore, not as susceptible to initial load relaxation as the end-loaded compression test), and the duration and total number of cycles were relatively small.

The maximum strain peaks do show a slight trend of strain relaxation with time, but such a small effect is difficult to attribute to a specific source such as specimen creep or fixture relaxation. The slope of the decreasing maximum strain trend correlates to a strain loss of only 1.3 microstrain per cycle. This is such a small value that more than the 51 cycles performed here are necessary to quantify it with certainty.

Finally, because the specimen was buckling slightly at the minimum strains, a minimum strain trend is not possible to determine reliably.

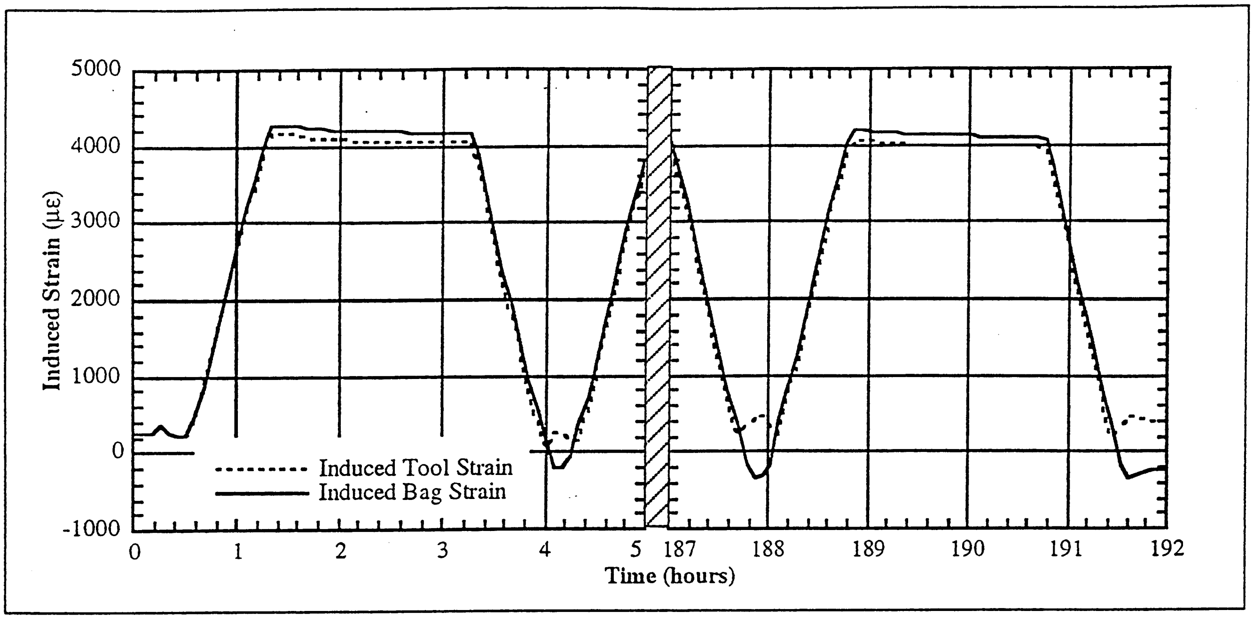


Figure 4.4.2-8. First and Last Cycle Strains

4.4.2.5 Discussion of Results

Several design parameters were verified by the single-cycle data. The preliminary cycle indicated that the predictions made in section 4.2 were very accurate (within 0.6%) and that the target tensile strains of 4,000 microstrain were met. Figure 4.4.1-4 showed the predicted and actual axial strains throughout the thermal cycle. The preliminary cycle also showed reasonable agreement between the back-to-back axial strain gages (better than 8% throughout the cycle), indicating reasonable alignment of the fixturing. The specimen grips performed well, with no evidence of specimen slippage under load. It was also apparent that a 2-hr soak at 350°F would be adequate to ensure that thermal equilibrium was reached.

At completion of the preliminary cycle, because little fixture or specimen refinement was necessary, a 50-cycle extended checkout test was started. The results of this 50 cycle test are discusscd below:

a. Specimen and fixture alignment properties are very good for the tension fixture.

b. The Intec specimen grips performed well, allowing easy specimen alignment, with no evidence of specimen slippage; however, they are the single most expensive component of the fixture.

c. The tension tube design was easy to assemble and align, provided symmetric loading, and demonstrated good heat transfer properties.

d. A higher prestrain (e.g., R = +0.1) to minimize the potential for specimen buckling at low temperatures should be used.

e. Little evidence of specimen creep or fixture relaxation was noted over the tension test duration of 51 cycles, at 3.25 hr per cycle. The slight observed effect amounted to a decrease of 1.3 microstrain per cycle.

4.5 FIXTURE REDESIGN AND FABRICATION

The prototype compression fixture (sec. 4.3.1) was redesigned because of problems encountered during fixture validation testing (sec. 4.4.1). These problems included alignment difficulties due to the reaction rod configuration, excessive thermal mass of the driver, and difficulty in applying symmetric load or adjusting the applied load. The reaction rod configuration was changed from two to three to minimize the torsional tendencies exhibited by the prototype fixture. Three rods also allow for load introduction adjustment in two directions, side to side and edge to edge. This ensures symmetric load introduction. The prototype fixture could only be adjusted in the edge-to-edge direction. Increasing the number of reaction rods also eliminates the need for alignment plates. The driver diameter was reduced to 0.75 in to minimize thermal mass and decrease the cycle time necessary to bring the fixture to equilibrium. The driver was also threaded to allow for a single-point load adjustment. In this way the magnitude of the applied load can be adjusted without affecting the load distribution, which is defined by the reaction rods.

Design analysis was carried out by Intec using a Boeing-supplied analysis spreadsheet (as used in sec. 4.1). The fixture load and strain analysis generated from this spreadsheet are shown in figure 4.5-1. Finite element analysis was also used by Intec to analyze the reaction rods. A photograph of the redesigned fixture is shown in figure 4.5-2. A drawing of this fixture is shown in figure 4.5-3. Drawings of the detail parts are contained in appendix C.

COMPRESSION FIXTURE LOAD AND STRAIN ANALYSIS

Reaction (Invar)		**Driver (304 SS)**		**Specimen (PMC)**		**Buckling Info**	
Length (in) =	17	Length (in) =	14	Length (in) =	3.00	Clamp height =	0.5
Area 3 rods (in^2) =	0.331	Area (in^2) =	0.442	Area (in^2) =	0.083	Fixity =	2
Modulus (psi) =	20.5E+6	Modulus (psi) =	28.5E+6	Modulus (psi) =	08.5E+6		
CTE (in/in) =	2.60E-06	CTE (in/in) =	9.70E-06	CTE (in/in) =	1.10E-06	**Fixture Geometry**	
1 rod dia (in)=	0.375	Diameter (in) =	0.750	Thickness (in) =	0.1664	Plate Thkns =	0.75
				Width (in) =	0.500		
		Delta T (°F) =	280				

Specimen Load (lbs) =	3382	BUCKLING	
Specimen Strain (E-6)=	4782 (no flex)	Effective Length (in) =	1
TRUE STRAIN (E-6)=	**4236** (includes flex)	Critical Load (lbs) =	16105
		Critical Strain (micro) =	22773
Fixture Strain =	269	Critical Stress (Ksi) =	194

Load = Temp.delta*{(CTE.s*L.s)-(CTE.r*L.r)+(CTE.d*L.d)}/{[L.s/(A.s*E.s))+(L.r/(A.r*E.r))+(L.d/(A.d*E.d)]}
Critical = PI()^2*E.s*W.s*t.s^3/(12*(G12)^2)
True Strain = Strain.s-(0.0244-0.0764*t.plate+0.0853*t.plate^2-0.0325*t.plate^3)*Strain.s/4000/L.s*1000000
3rd order polynomial obtained by FEM. Cases run using load of 4000lbs; normalized to actual load as above.

Variable Names	
L = Length	.s = Specimen
A = Area	.r = Reaction
E = Modulus	.d = Driver

The fixture must be capable of 2000 and 4000 microstrain. Invar and driver were cut down by 8.5 inches to accommodate 2000 strain level.

Figure 4.5-1. Compression Fixture Load and Strain Analysis

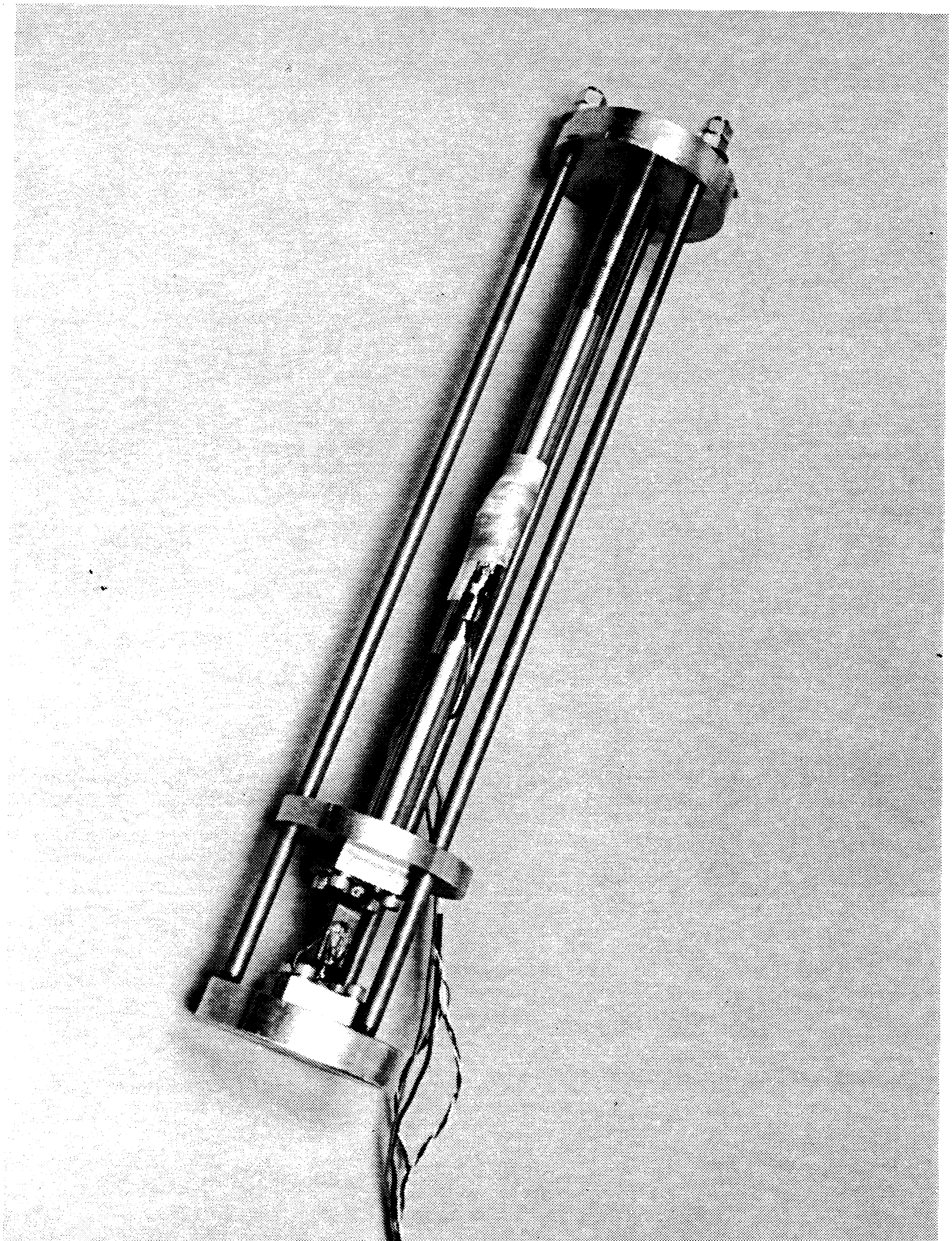
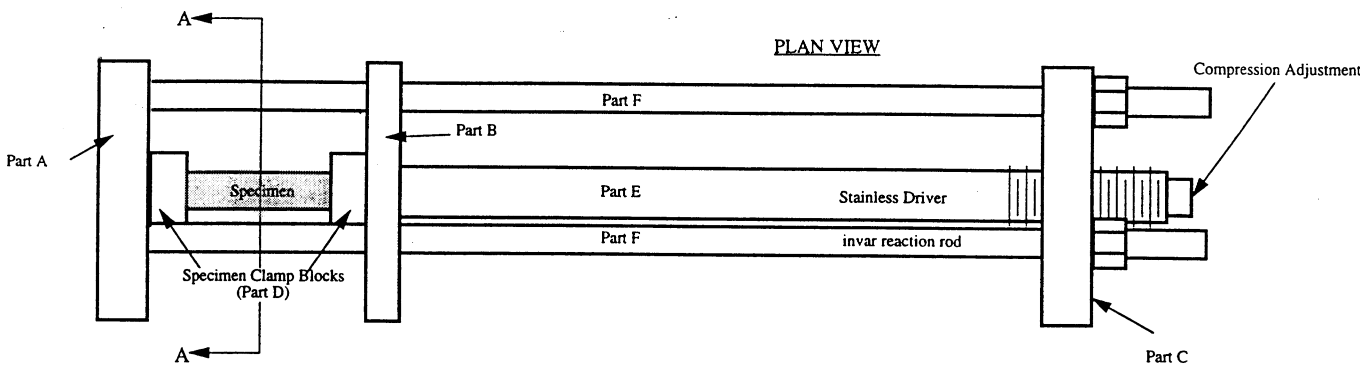
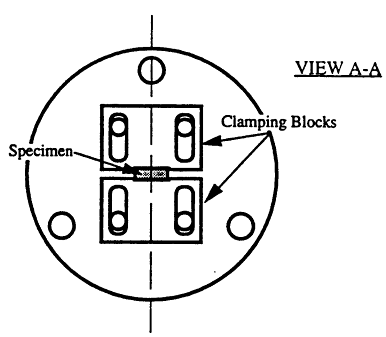


Figure 4.5-2. Redesigned Compression Fixture





PRINCIPLE OF OPERATION

Three invar rods (Part F) are threaded into Part A, and Parts B and C slide along the rods. Part C is located using nuts threaded onto the invar rods. Part E, the driver, is butted against Part B, and threaded into part C. As the assembly is heated, the stainless steel of Part E expands approximately 9 times farther than the invar rods, thereby providing a compressive load to the specimen, which is held in place between Parts A and B by the clamping blocks of Part D.

Figure 4.5-3. Drawing of Redesigned Compression Fixture

The tension fixture design remained essentially the same as the prototype. A photograph of the current tension fixture is shown in figure 4.5-4. A drawing of this fixture is shown in figure 4.5-5. Drawings of the detail parts are contained in appendix D. The mechanical grips used to hold specimens in this fixture were discussed in section 4.4.2.2.

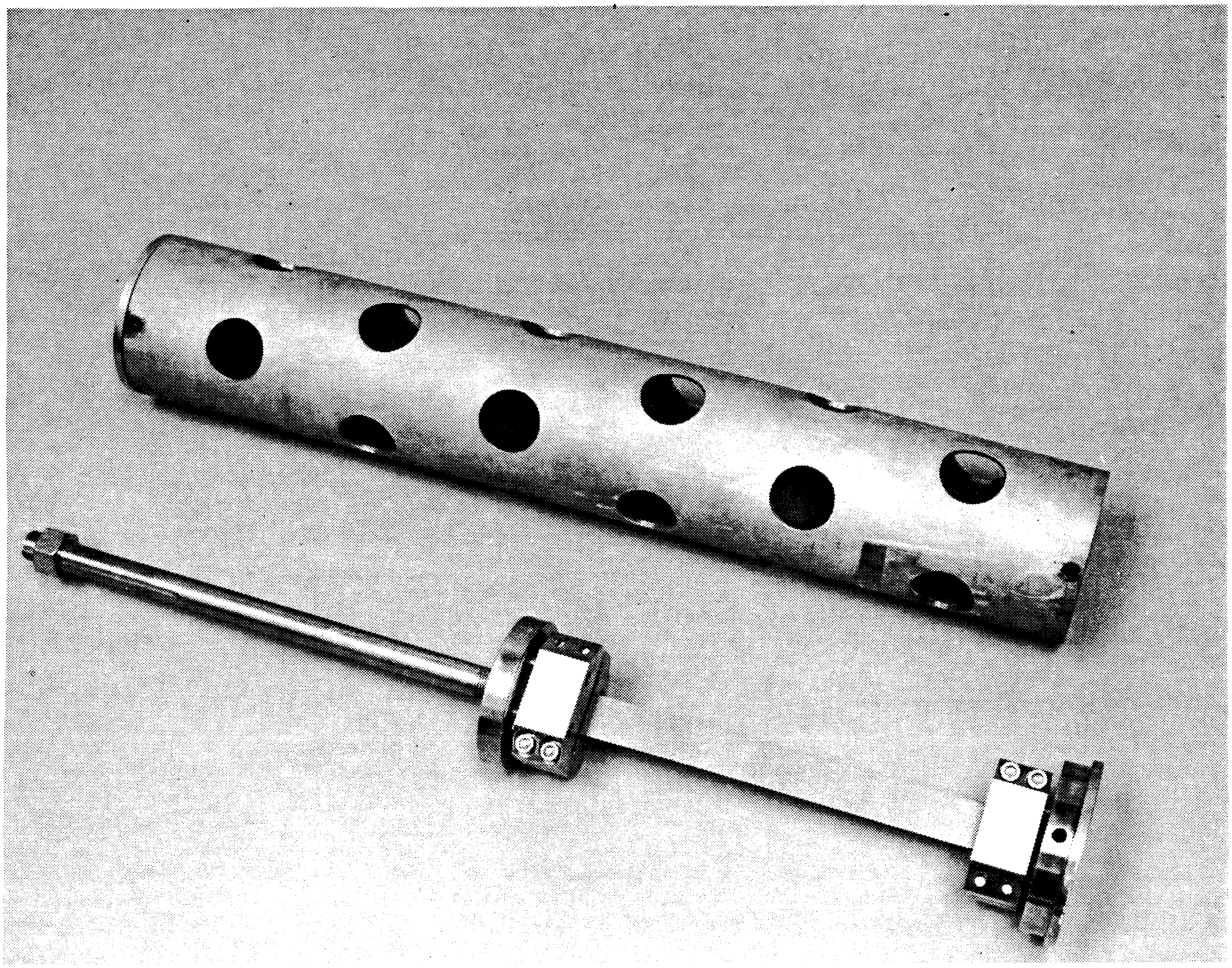
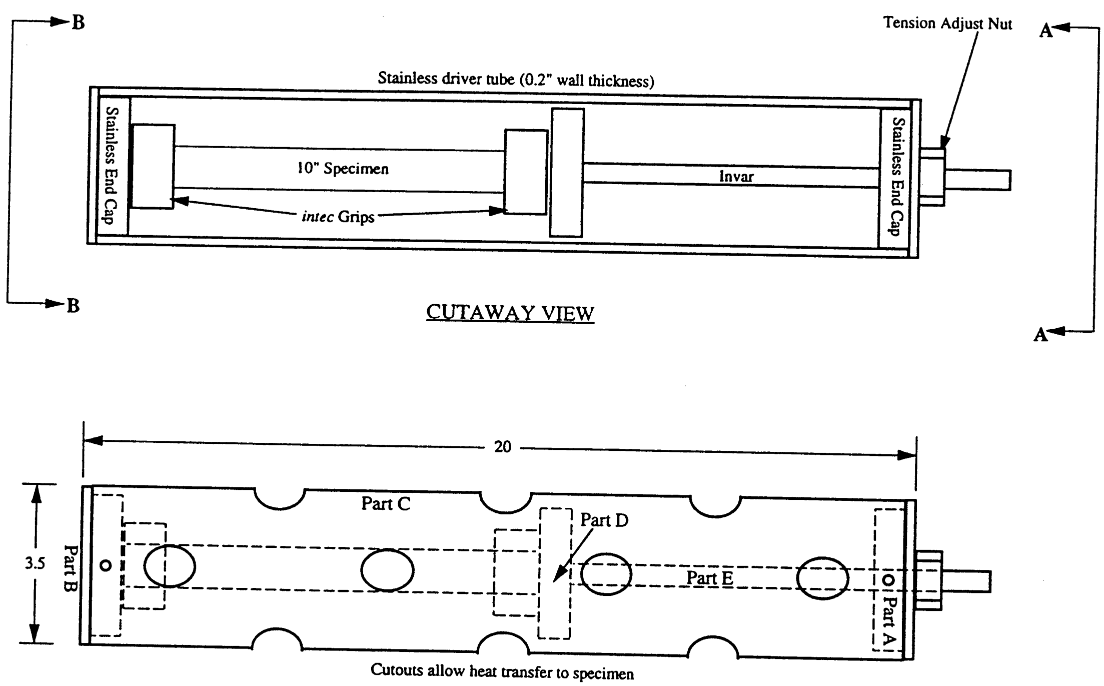


Figure 4.5-4. Current Tension Fixture



PRINCIPLE OF OPERATION
A test specimen is mounted in a set of grips, which mount to Parts D and B. Part E is constructed of invar steel, which is a low thermal expansion steel. Part E is mounted to Part D, and is restrained by a nut against Part A. As Part C expands with increasing temperature at a rate of about 9 times that of the invar and the specimen, a tensile load is applied to the specimen in-phase with rising temperature. This fixture will be placed in a thermally cycling chamber for up to 7 years to apply cyclic tensile loads to graphite specimens. (Note that the grip assemblies are not included in these drawings.)

Figure 4.5-5. Drawing of Current Tension Fixture

Numerous tension and compression fixtures and grips were fabricated by Intec. Figure 4.5-6 provides the fixture quantity and identification and whether these fixtures are being leased or were purchased.

Tension Fixture ID (TAT)	**Own/ Lease**	**Mech. Grip ID**	**Own/ Lease**	**Comp. Fixture ID (TAC)**	**Own/ Lease**
TAT-2-01	own	MGR-1-01	own	TAC-2-09	own
TAT-2-02	own	MGR-1-02	own	TAC-2-10	own
TAT-2-03	own	MGR-1-03	own	TAC-2-11	own
TAT-2-04	own	MGR-1-04	own	TAC-2-12	own
TAT-2-09	lease	MGR-1-05	own	TAC-2-13	lease
TAT-2-10	lease	MGR-1-06	lease	TAC-2-14	lease
TAT-2-11	lease	MGR-1-07	lease	TAC-2-15	lease
TAT-2-12	lease	MGR-1-08	lease	TAC-2-16	lease
TAT-2-13	lease	MGR-1-09	lease	TAC-2-17	lease
TAT-2-14	lease	MGR-1-10	lease	TAC-2-18	lease
TAT-2-15	lease	MGR-1-11	lease	TAC-2-19	lease
TAT-2-16	lease	MGR-1-12	lease	TAC-2-20	lease
TAT-2-17	lease	MGR-1-13	lease	TAC-2-21	lease
TAT-2-18	lease	MGR-1-14	lease	TAC-2-22	lease
TAT-2-19	lease	MGR-1-15	lease	TAC-2-23	lease
TAT-2-20	lease	MGR-1-16	lease	TAC-2-24	lease
		MGR-1-17	lease		
		MGR-1-18	lease		
		MGR-1-19	lease		
		MGR-1-20	lease		

Figure 4.5-6. Tension and Compression Fixure Inventory

5.0 HYDRAULICALLY ACTUATED FIXTURES

5.1 FIXTURE DESIGN

Intec designed and fabricated hydraulic fixtures for use in chamber No. 3 (350°F). (Section 8.0 contains the chamber and hydraulic manifold design.) A maximum of 25 hydraulic fixtures can be thermally cycled in this chamber. Hydraulic actuators can be independently mounted to (and removed from) the chamber front enclosure. A drawing of the tensile hydraulic fixture and mounted hydraulic actuator is shown in figure 5.1-1. Drawings of the detailed parts are contained in appendix E.

A room temperature hydraulic system was also fabricated. This setup allows for load testing of materials without thermal cycling. Both composites and adhesives can be tested using this setup (hydraulic fixtures for adhesives were fabricated under MDOC Task 11). The design specifications are as follows:

Actuator: Enerpac double-acting Model BMD-70251
Loads: 15,440 lb compression, 9,120 lb tension
Max stroke: 0.98 in
Operating pressure: 5,000 psi
Response: spikes up to 1 Hz

Control: Digital PID controllers (Watlow 982)
Valving: coupled directional and proportional mechanical valves (4 zones)

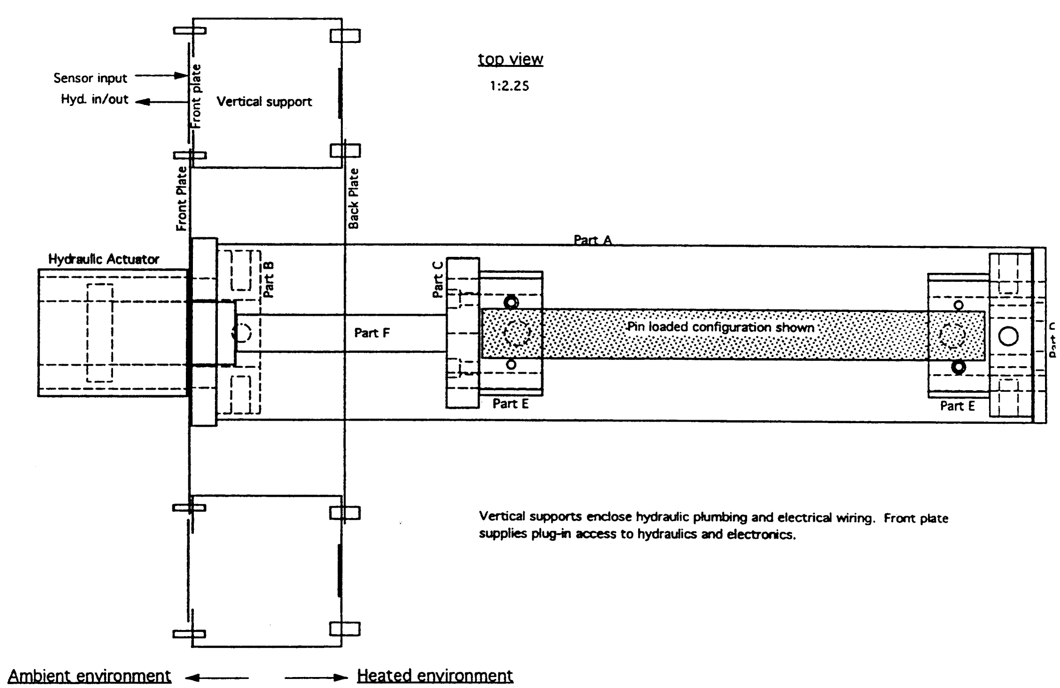


Figure 5.1-1. Hydraulically Actuated Fixture Configuration

5.2 FIXTURE FABRICATION

Four hydraulic fixtures were fabricated in accordance with figure 5.1-1. The fixture identification numbers and lease or own status are given in figure 5.2-1.

Hydraulic Fixture ID (HAR)	Own/Lease
HAR-1-01	own
HAR-1-05	lease
HAR-1-06	lease
HAR-1-07	lease

Figure 5.2-1. Hydraulic Fixture Inventory

5.3 FIXTURE VALIDATION

Validation testing of the hydraulic fixtures is included in section 8.3.2, "Chamber No. 3 Hydraulic Spectrum and Load Equivalence Test."

6.0 CONCEPT FOR 6-IN COMPRESSION FIXTURE

A compression fixture that could accommodate a 6-in-wide specimen was developed to increase test capability of a single fixture. A 6- by 6-in laminate could be cut into approximately 24 compression specimens for residual strength testing. This many test specimens would require 24 of the thermal cycling fixtures described in section 4.5. By cycling multiple 6-in compression fixtures, 25 per chamber (sec. 8.0), approximately 600 specimens per chamber can be tested simultaneously.

The 6-in compression fixture design is based on the CTE concept described in section 4.0. Because of the larger specimen cross section, two invar reaction rods (instead of one) and a stainless steel I-beam driver (instead of three rods) are used. A drawing of this concept is shown in figure 6.0-1.

Fixture fabrication was not carried out under this contract, but may be considered for the HSR II, Task 15 study.

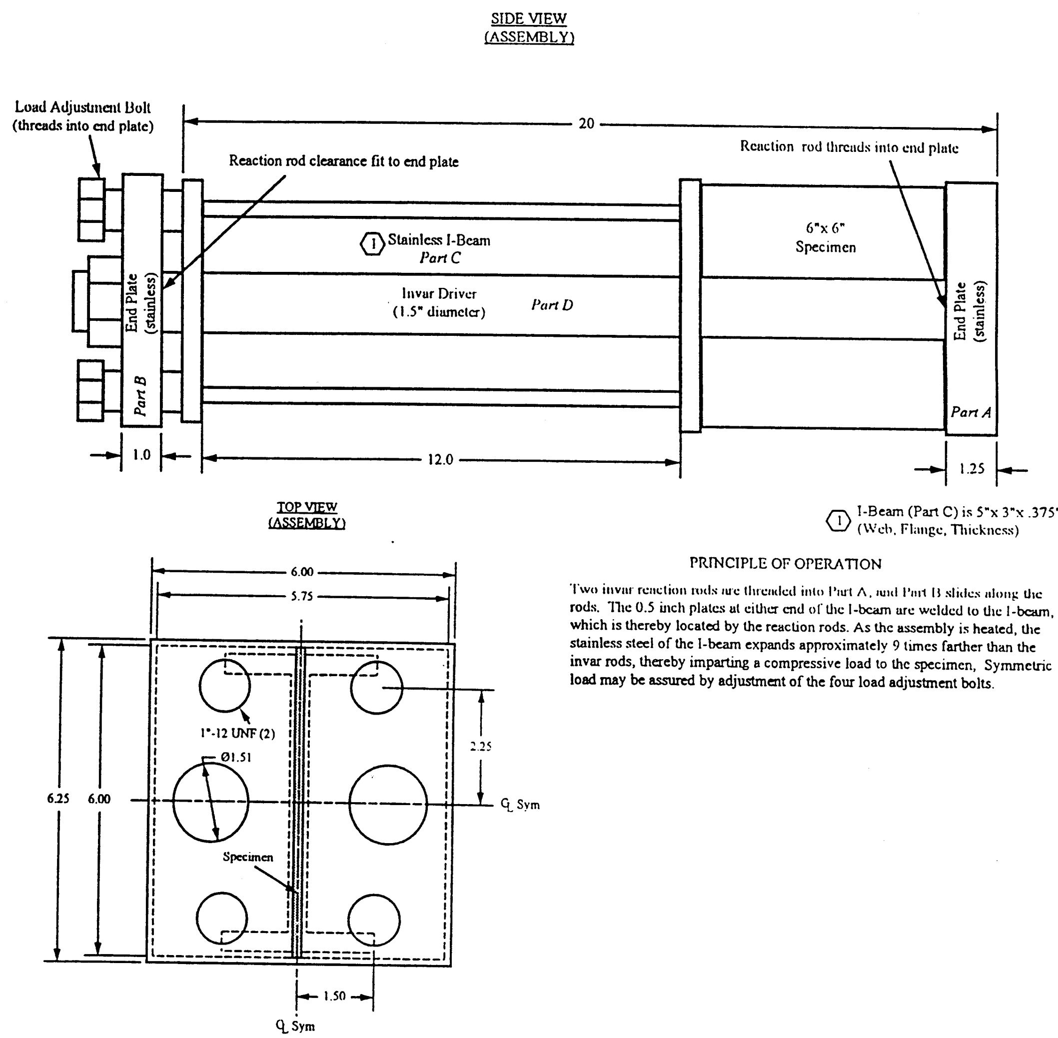


Figure 6.0-1. Drawing of 6-in Compression Fixture Concept

The Excel spreadsheet used in section 4.0 for fixture design optimization was also used for the 6-in compression fixture. The load and strain analysis for the fixture concept is shown in figure 6.0-2.

COMPRESSION FIXTURE LOAD AND STRAIN ANALYSIS					
Reaction (invar)		**Driver (304 SS)**		**Specimen (PMC)**	
Length (in) =	20	Length (in) =	13	Length (in) =	6.00
Area 2 rods (in^2) =	3.534	Area (in^2) =	4.125	Area (in^2) =	1.080
Modulus (psi) =	20.5E+6	Modulus (psi) =	28.5E+6	Modulus (psi) =	08.5E+6
CTE (in/in) =	1.50E-06	CTE (in/in) =	9.70E-06	CTE (in/in) =	1.10E-06
1 rod dia (in)=	1.500	Web (in) =	5.0	Thickness (in) =	0.18
		Flange (in) =	3.0	Width (in) =	6.000
		Thickness (in) =	0.375		
		Delta T (°F) =	280		
Specimen Load (lbs) =	27644				
Specimen Strain (E-6)=	3011 (no flex)				

Load = Temp.delta*{(CTE.s*L.s)-(CTE.r*L.r)+(CTE.d*L.d)}/{[L.s/(A.s*E.s))+(L.r/(A.r*E.r))+(L.d/(A.d*E.d)]}
Strain = 1000000*Load.s/(A.s*E.s)

VARIABLE NAMES

L = Length	.s = Specimen	CTE = Coef. Thermal Expansion
A = Area	.r = Reaction	
E = Modulus	.d = Driver	

Figure 6.0-2. Strain and Load Analysis for 6-in Compression Fixture

7.0 LOW-COST DISPLACEMENT MEASUREMENT CONCEPT

Current testing plans incorporate the use of strain gages to verify that fixtures are transferring predetermined loads to the test specimens. Based on these data, mechanical adjustments to the fixture (tightening or loosening of the reaction rod nuts) can be made if warranted. Because of temperature degradation effects, strain gages may not be a viable strain measurement method for long-term environmental testing. Alternative low-cost displacement measurement concepts were investigated for accurately measuring and adjusting the loads on the driver rods (ref. 4). Although these methods were not used for this contract, they may be considered for HSR II, Task 15 work. These methods are as follows:

a. Linear voltage displacement transducer.
b. Capacitive proximity sensor.
c. Ultrasound.
d. Laser displacement method.
e. Direct force measurement.

Linear Voltage Displacement Transducer (LVDT). Strain measurements could be made using an LVDT. High-temperature LVDTs are available but very expensive. This cost would be multiplied by the number of fixtures in test, as a dedicated LVDT would be required for each fixture. Tooling modifications would also be required for each fixture.

Capacitive Proximity Sensor. Capacitive proximity sensors have the same drawbacks as the LVDTs in that special high-temperature sensors would be required for each fixture. Calibration and mounting hardware would also be required. It is estimated that proximity sensors would be just as expensive as using LVDTs to monitor displacements.

Ultrasound. Ultrasonic methods could be used to measure the displacement of the thermal fixture driver rods. This would require extensive calibration to accurately record the length of the driver rod at elevated temperature. Noise due to the interference produced by the large aspect ratio of the fixture driver, as well as the threads present on the fixture driver, would also need to be filtered out. It may not be possible to filter out this noise, depending on its severity. To obtain an optimized ultrasonic signal, the rod ends must be parallel, smooth (125 surface finish), and perpendicular to the ultrasonic signal. This requires machining modifications for each fixture. It is estimated that an ultrasonic system, including calibration and implementation, would cost only slightly less than either the LVDT or proximity sensor methods.

Laser Displacement Method. Laser measurement systems are available off the shelf and have reported resolution as fine as 10 microstrain at ambient conditions. Unfortunately, these affordable laser systems would not be able to withstand the high temperatures used for durability testing. At high temperatures the laser would need to be moved away from the fixture (approximately 10 in), creating sighting problems. This problem is amplified by the need to move the laser from fixture to fixture. This would require a very accurate triaxial positioning system. The cost of this system is estimated to be greater than the three other systems discussed above.

Direct Force Measurement. Direct force measurement uses equipment to measure the force on the driver directly. Schematics of this system for the compression and tension fixtures are shown in figures 7.0-1 and 7.0-2, respectively. A hydraulic ram applies a load, which is transferred to the fixture using threaded or smooth extension rods. The loads can be measured using pressure transducers placed in line between the ram and the hydraulic pump. The hydraulic pump could be automatically activated and controlled by a PID controller. Once the driver rod has been loaded to the specified level (equivalent to desired specimen load at temperature), the load on the nut will have been removed. Therefore, if the nut is loose, indicating the loading in the test fixture has relaxed over time, it could be retightened by hand. The advantage of this system is that the load adjustment is simple versus the laser or ultrasonic systems. For these systems, if a length measurement indicates inadequate loading, the tightening of the nut would be difficult, as the entire load is still carried by the nut. The nut would have to be tightened at room temperature and then verified once the fixture had been reheated. The overall cost for the direct force measurement system is estimated to be lower than all of the systems discussed. This lower cost, combined with direct measurement and simple load adjustment, makes it the recommended measurement system for future work (HSR II, Task 15).

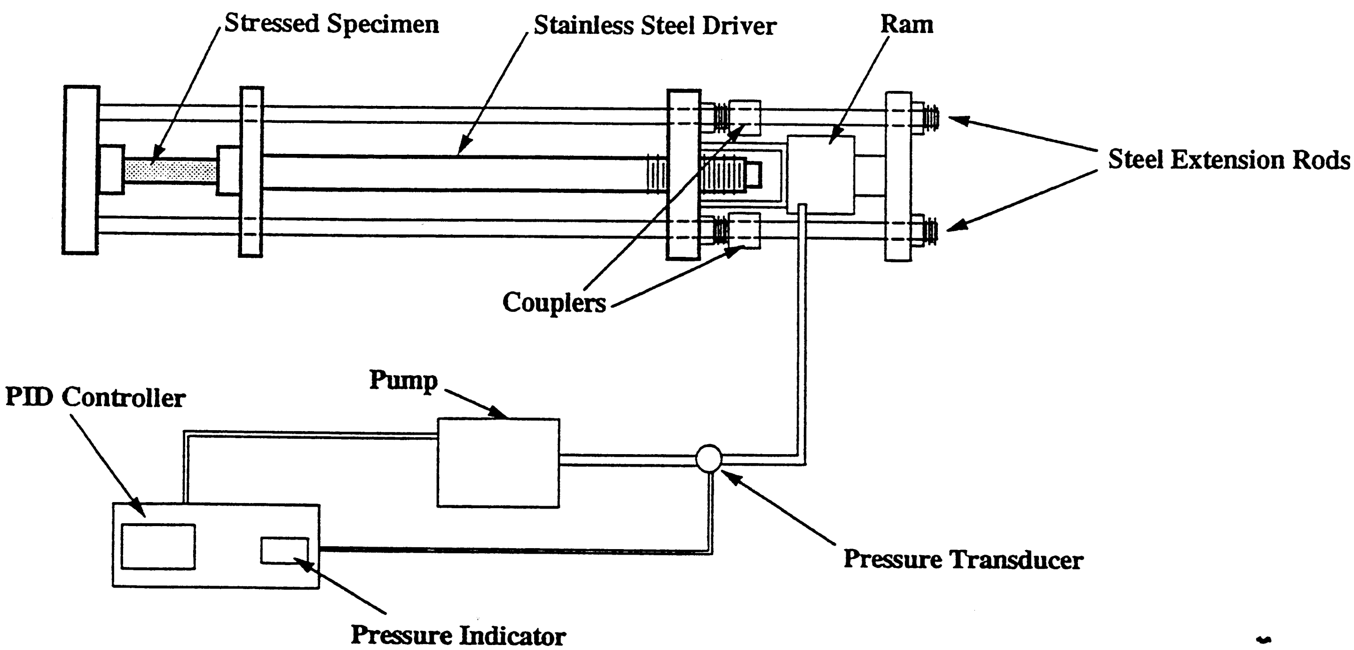


Figure 7.0-1. Direct Force Application Method Used on the Compression Fixture

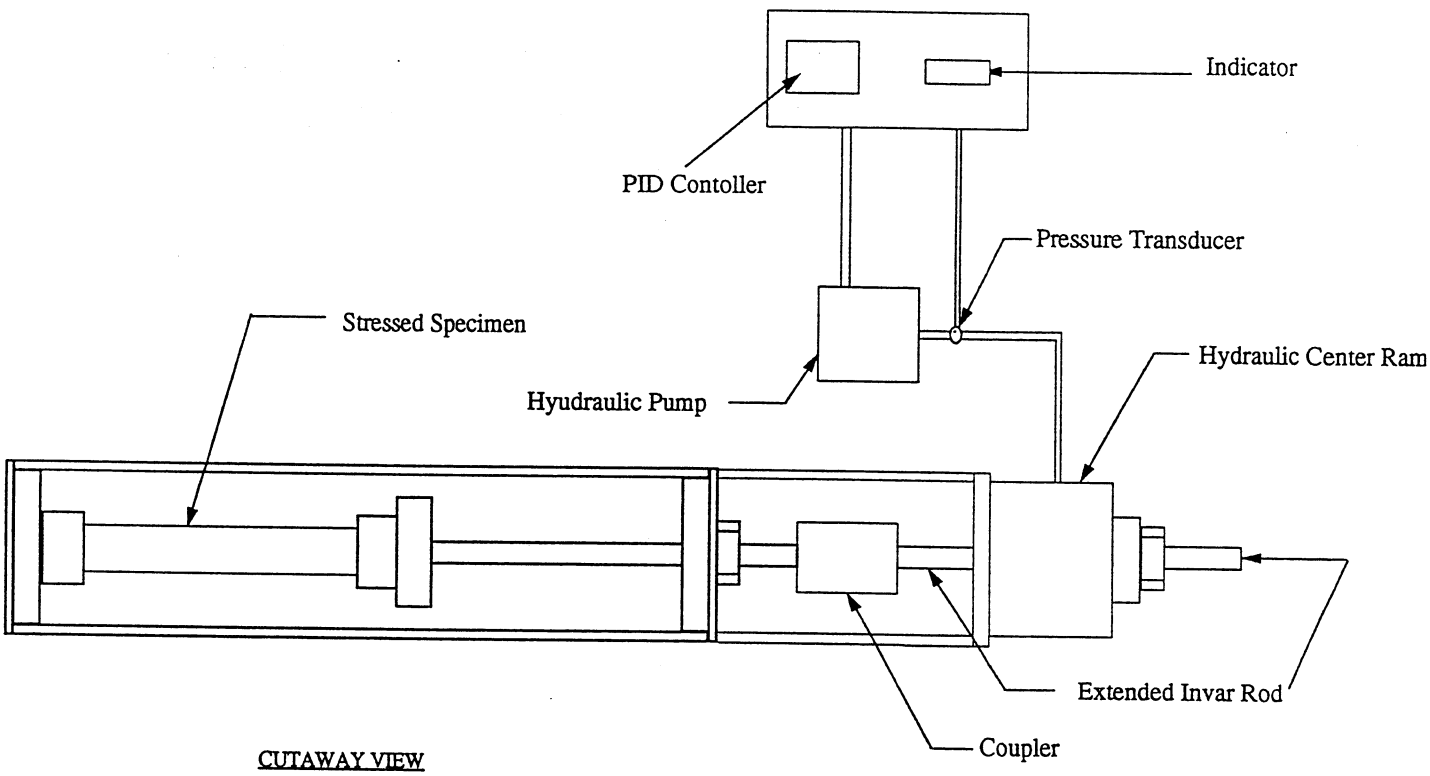


Figure 7.0-2. Direct Force Application Method Used on the Tension Fixture

8.0 TEST CHAMBERS

8.1 CHAMBER CONFIGURATIONS

Three thermal cycling chambers were designed and built by Intec. All of the chambers are modified Blue M model EM-326EX 600°F electrical ovens with inside dimensions of 48 by 24 by 48 in. Two chambers were constructed for 350°F (chamber No. 1) and 300°F (chamber No. 2) thermal cycling. The third chamber was constructed for 350°F (chamber No. 3) thermal and hydraulic cycling. All of the chambers had the original doors removed and replaced with 25-cell modular front enclosures (fig. 8.1-1). This enclosure allows individual access to all 25 fixtures, and for chamber No. 3, it also allows mounting the individual fixture hydraulic actuators. A closeup photograph of an individual cell, containing a fixture, is shown in figure 8.1-2.

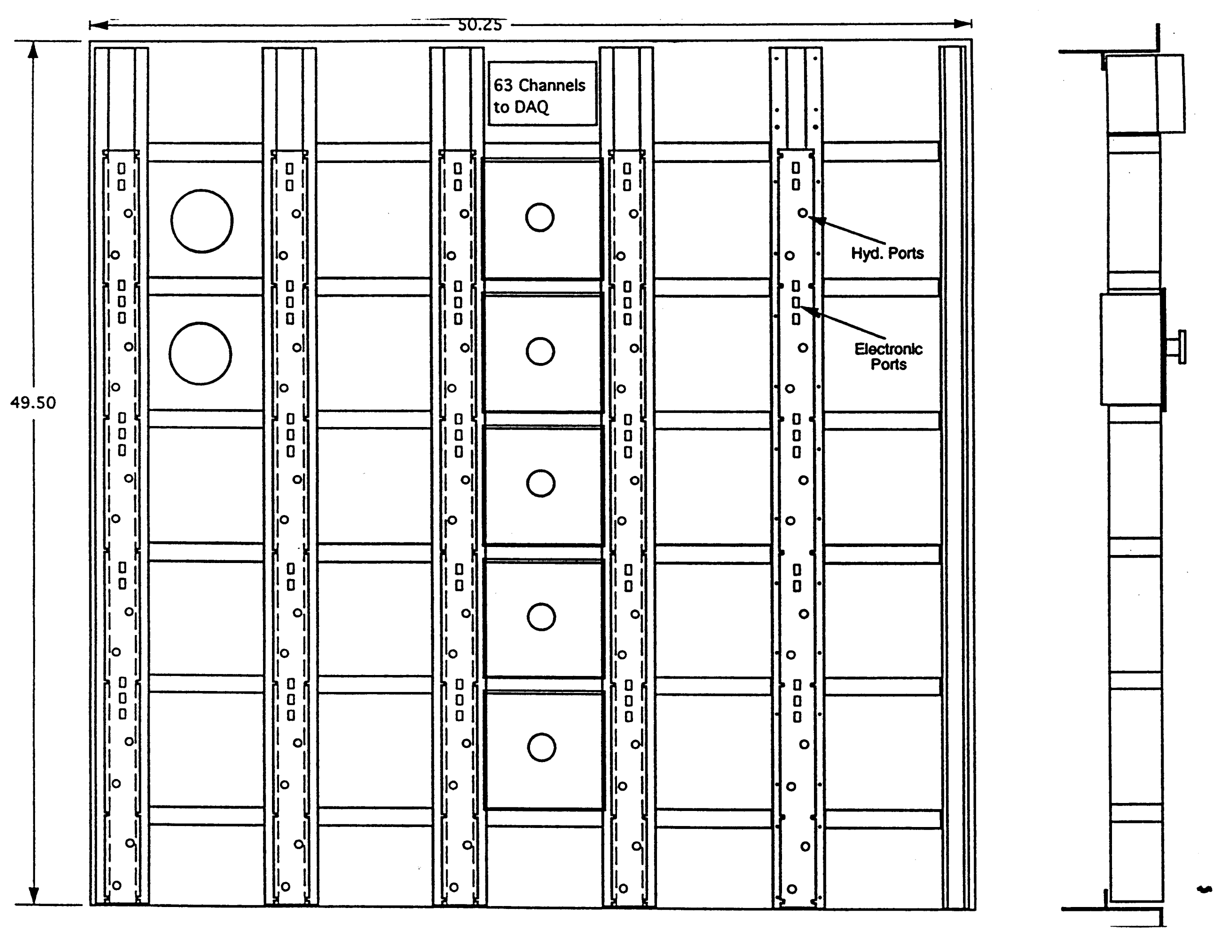


Figure 8.1-1. Thermal Chamber Front Enclosure (25 Cells)

Figure 8.1-2. Front Enclosure Cell Closeup With Fixture

Other modifications were made to the ovens, including heating elements, flow ducting, cooling system, controller and power electronics, overtemperature and undertemperature protection devices, and temperature sensing thermocouples. Ambient air is used during the cooldown until the required cooldown rate can no longer be maintained. LN2 flow is then activated for the rest of the cooldown cycle. Figure 8.1-3 provides a schematic of the chamber system.

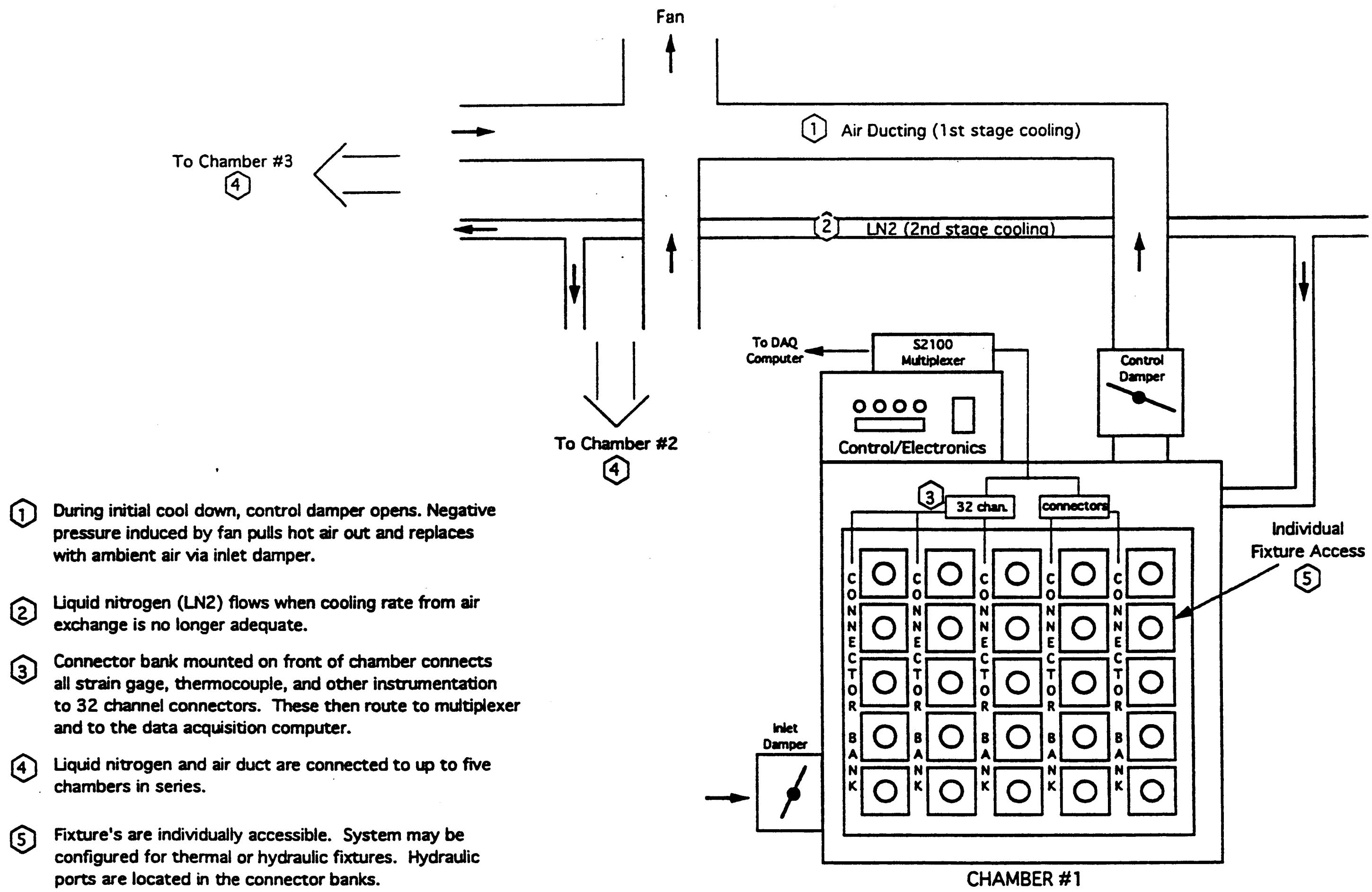


Figure 8.1-3. Thermal Chamber System Schematic

A photograph of all three chambers is shown in figure 8.1-4. On the far left in the figure is chamber No. 3 with 10 hydraulic actuators in place. The hydraulic actuator mounting schematic was shown in figure 5.1-1. The hydraulic control system is capable of providing two separate zones of control with a maximum frequency of 1 Hz. The manifold system is capable of distributing 18,000 lb tension or compression to each cell. A schematic of the hydraulic system for chamber No. 3 is shown in figure 8.1-5.

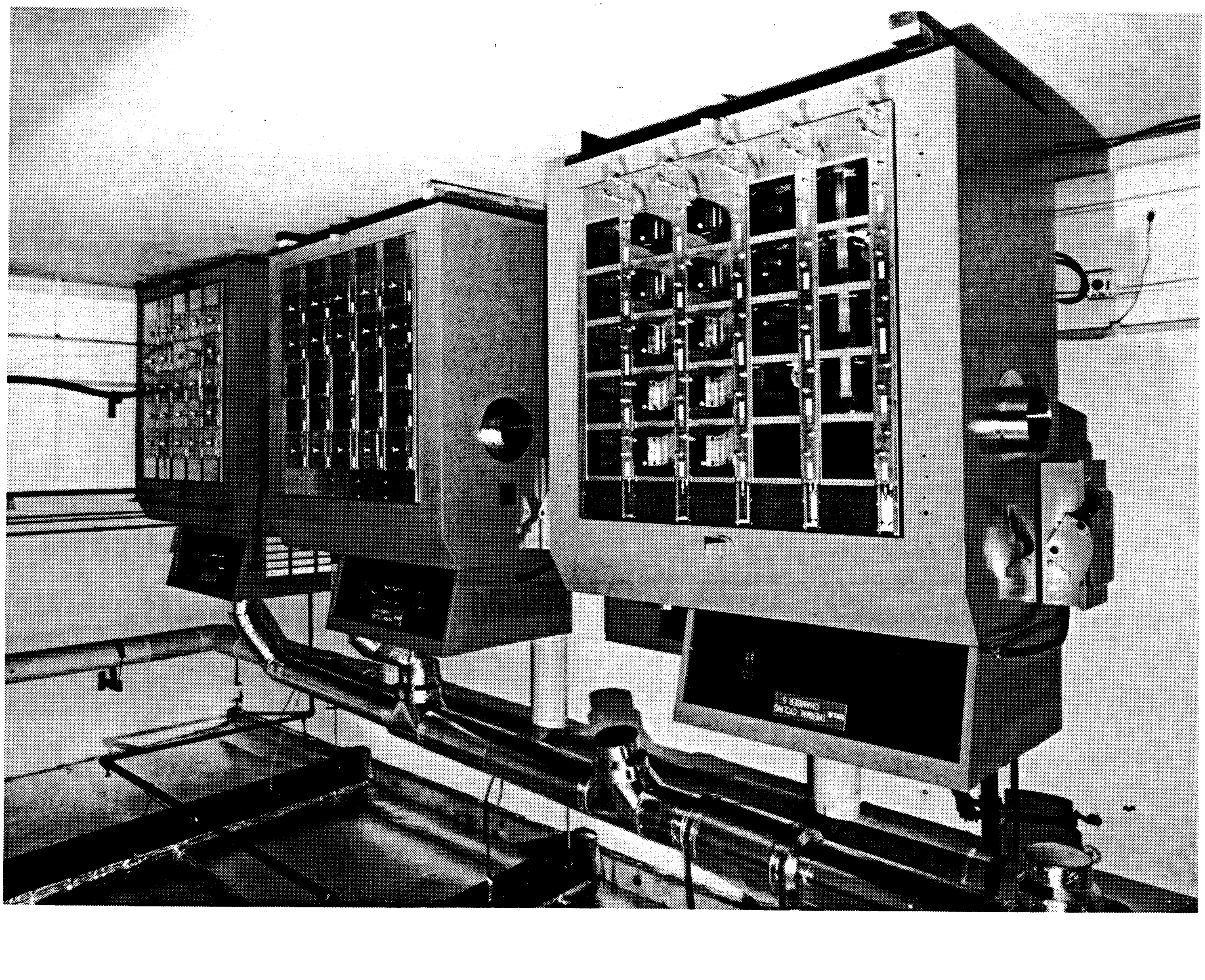


Figure 8.1-4. Thermal Cycling Chambers

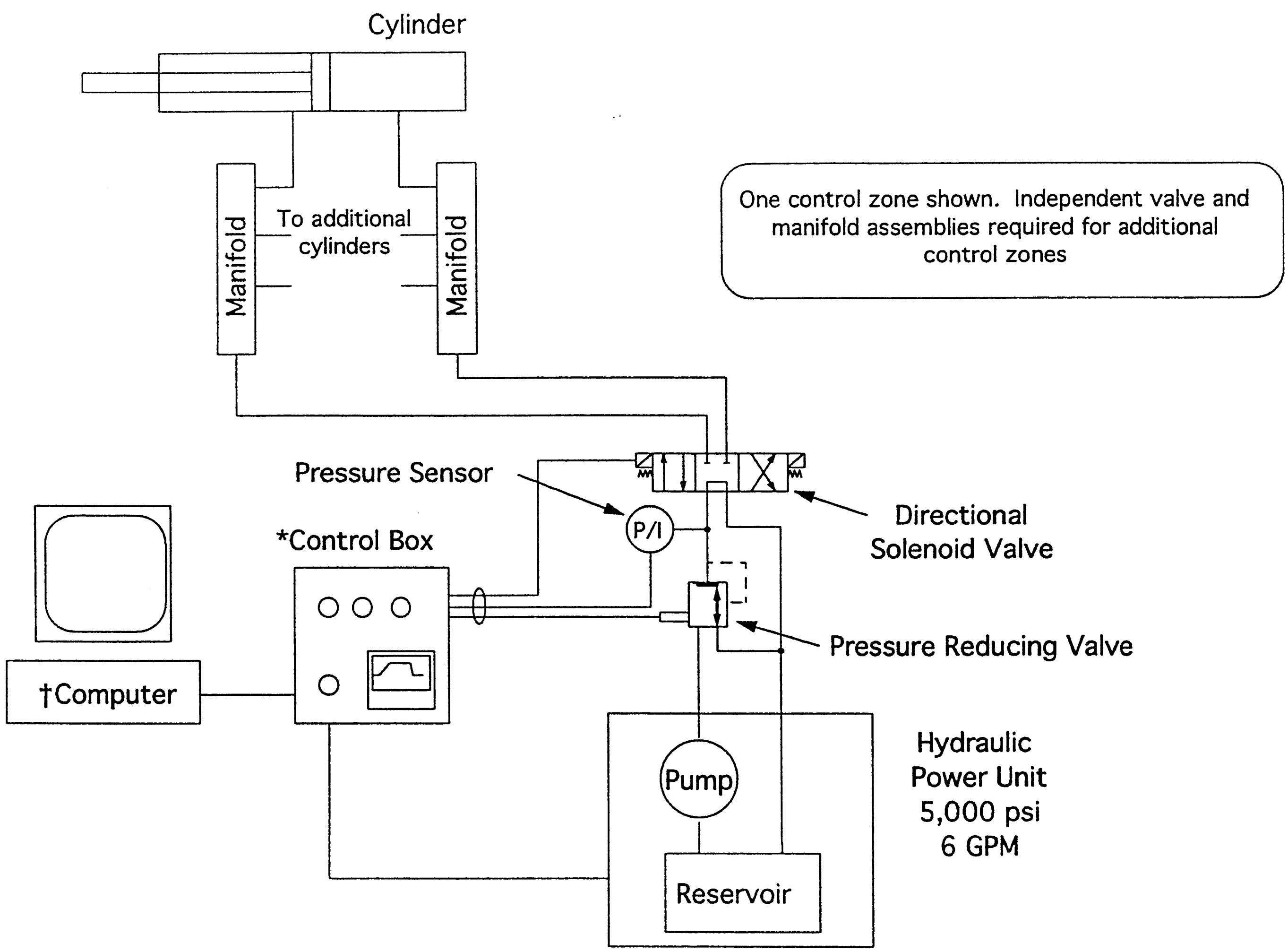


Figure 8.1-5. Hydaulic System Schematic

8.2 DATA ACQUISITION AND INSTRUMENTATION

The data acquisition system is composed of an Intec-produced hardware and software system that can obtain data from up to 63 channels per chamber. The system uses an i486-based personal computer equipped with a National Instruments M10-16 A to D board and a multichannel RS-232 controller board. This computer is linked to an S2100 conditioning multiplexer produced by Intec. The RS-232 controls multiplexer switching to an S2000 conditioner and two 32-channel terminal blocks for 64 channels of strain and/or temperature. (If any thermal data are taken, one channel must be used for cold junction compensation, thereby giving 63 available channels). Data acquisition software uses Intec software written on the Labview platform (a National Instruments code). Figure 8.2-1 shows the data acquisition system.

All thermocouples used to monitor chamber, fixture, and specimen temperatures, as well as those used for chamber feedback and overtemperature control, were type K. The thermocouple wire was calibrated by Pyrometrics of Seattle.

All strain gages were calibrated independently, based on the gage's published gage factor and the bridge completion electronic circuitry used. The electronic balance and tare values required to balance and set the gain for the Wheatstone bridge circuitry for each gage are recorded at the beginning of the test. This ensures that every gage can be rebalanced and configured should the electronics or data acquisition software be interrupted. Specific strain gage types are discussed in section 8.3.

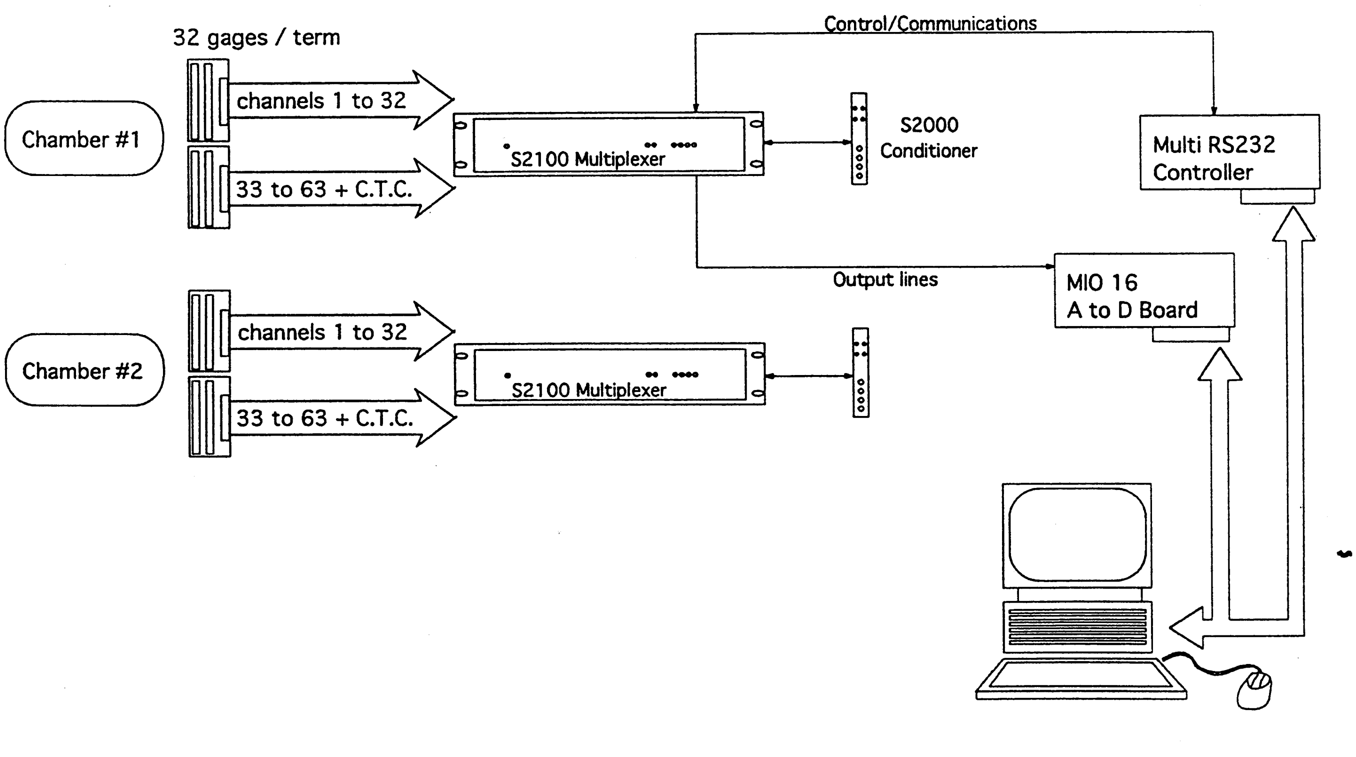


Figure 8.2-1. Data Acquisition System

8.3 CHAMBER VALIDATION

8.3.1 Chamber No. 1 100-Cycle Test

The purpose of the 100-cycle checkout was to (1) evaluate specimen geometry and instrumentation suitability for long-term thermal cycling and (2) evaluate temperature profiles of fixtures and specimens during cycling.

For this test a chamber comparable to chamber No. 1, but with the original doors (rather than the 25-cell front enclosure), was used, as chamber Nos. 1, 2, and 3 were still being fabricated. There were 25 fixtures cycled, 8 with test specimens (4 compression and 4 tension). Initially, straight-sided, 16-ply quasi-isotropic K3B/IM7 tension specimens (1 by 10 in) were used. These were gripped with 70 in-lb of torque. Because specimens began slipping at 3,800 microstrain, this torque was increased to 100 in-lb. Although slipping did not occur during the next 100 cycles, it was decided that there was a risk of slippage during a 1,000- to 2,000-cycle durability test. Therefore, a dogbone-shaped specimen was selected to increase the specimen's gripped area. The final specimen geometry is a 10-in-long specimen with 1.5-in endwidth and a 1- by 3.5-in gage section. Final grip torque used was 120 in-lb. The tension specimen geometry with gage is shown in figure 8.3-1. A 32-ply quasi-isotropic K3B/IM7 compression specimen (0.5 by 3.0 in) was used for the 100-cycle test. The compression specimen geometry with gage is also shown in figure 8.3-1.

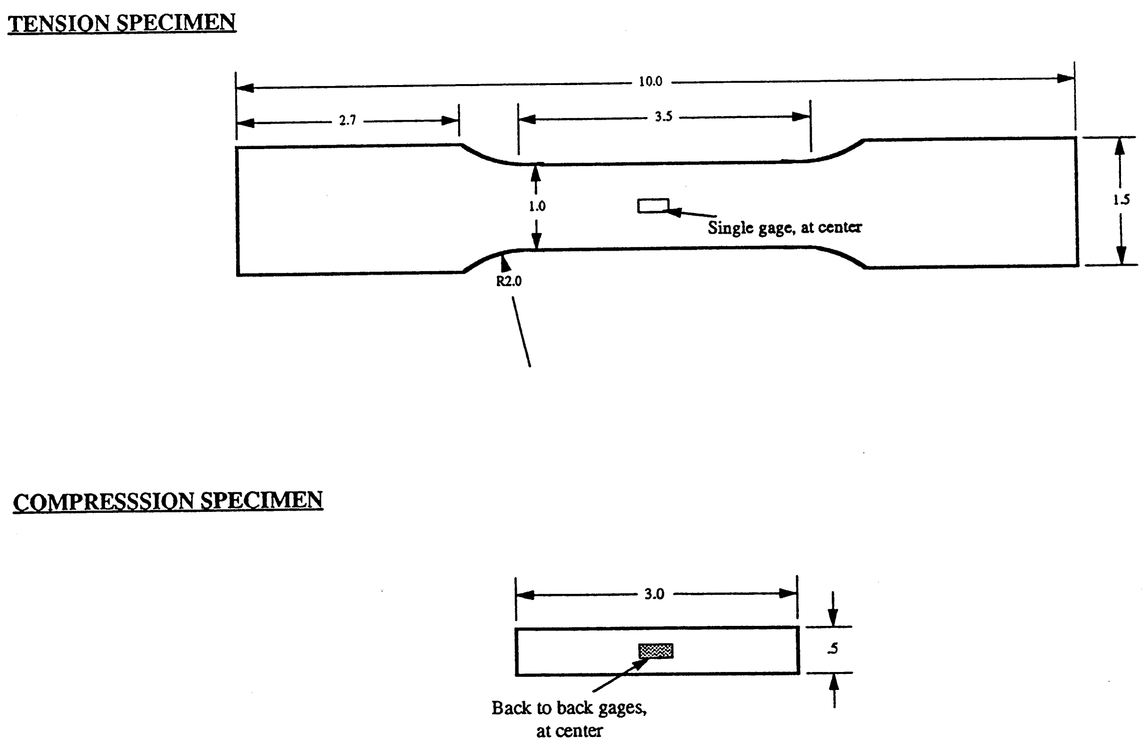


Figure 8.3-1. Tension and Compression Specimen Configurations

Initially, constantan strain gages and GA-61 adhesive and protective coating were used on the tension and compression specimens. This decision was based on Measurements Group's (strain gage manufacturer) recommendation. After only a few thermal cycles, several compression gages failed because of cracking of the GA-61 coating. Discussions with Measurements Group revealed that GA-61 was not a high-temperature sealant, as first reported. M-Bond 600 adhesive and Loctite Ultra-Copper (780°F room temperature vulcanized (RTV)) sealant were then recommended and used for 100 cycles without any problems. Strain readings, however, did demonstrate a gradually increasing indicated strain. Examples of this drift for the tension and compression specimens are shown in figures 8.3-2 and 8.3-3.

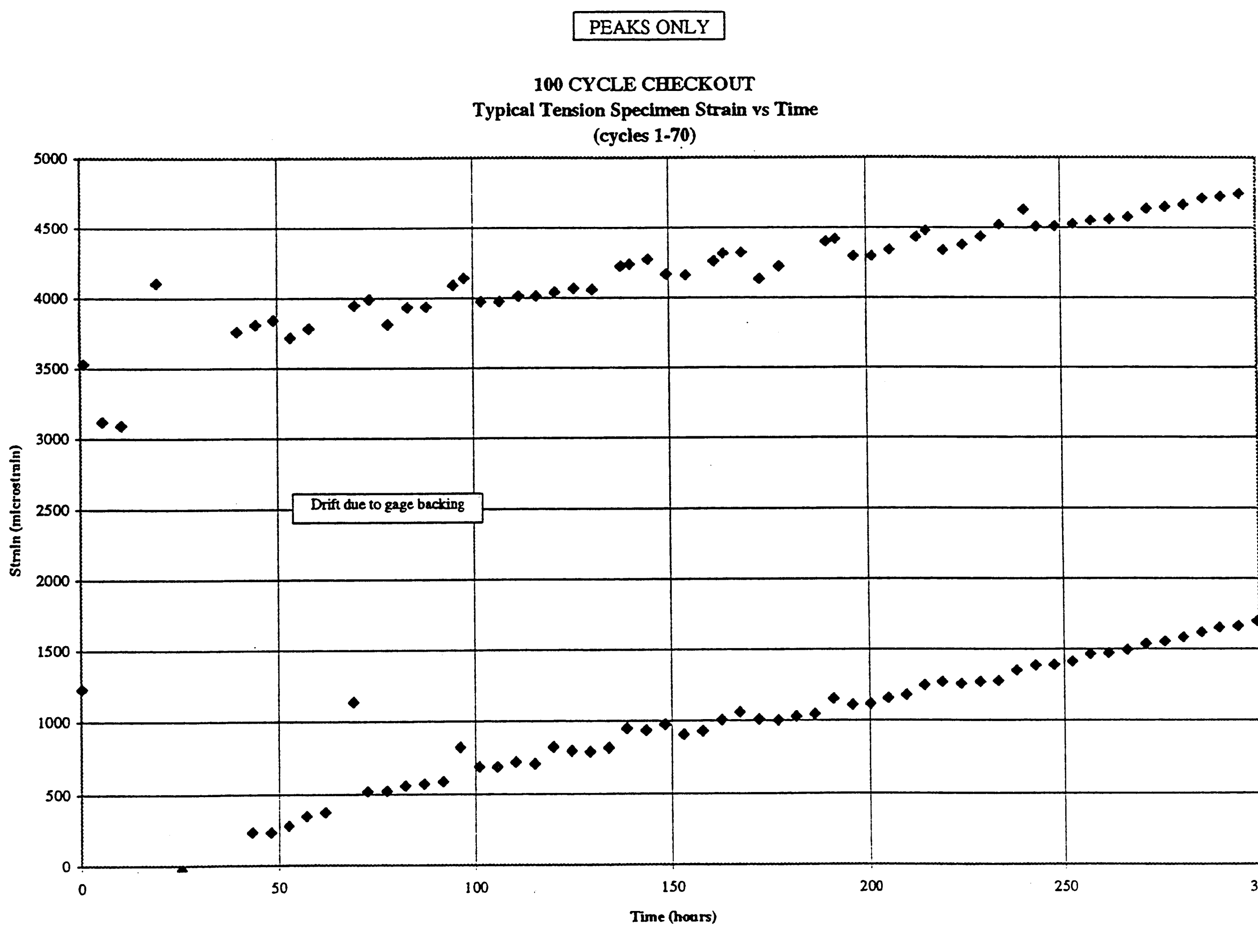


Figure 8.3-2. Tension Strain Profile (Cycles 1 to 70)

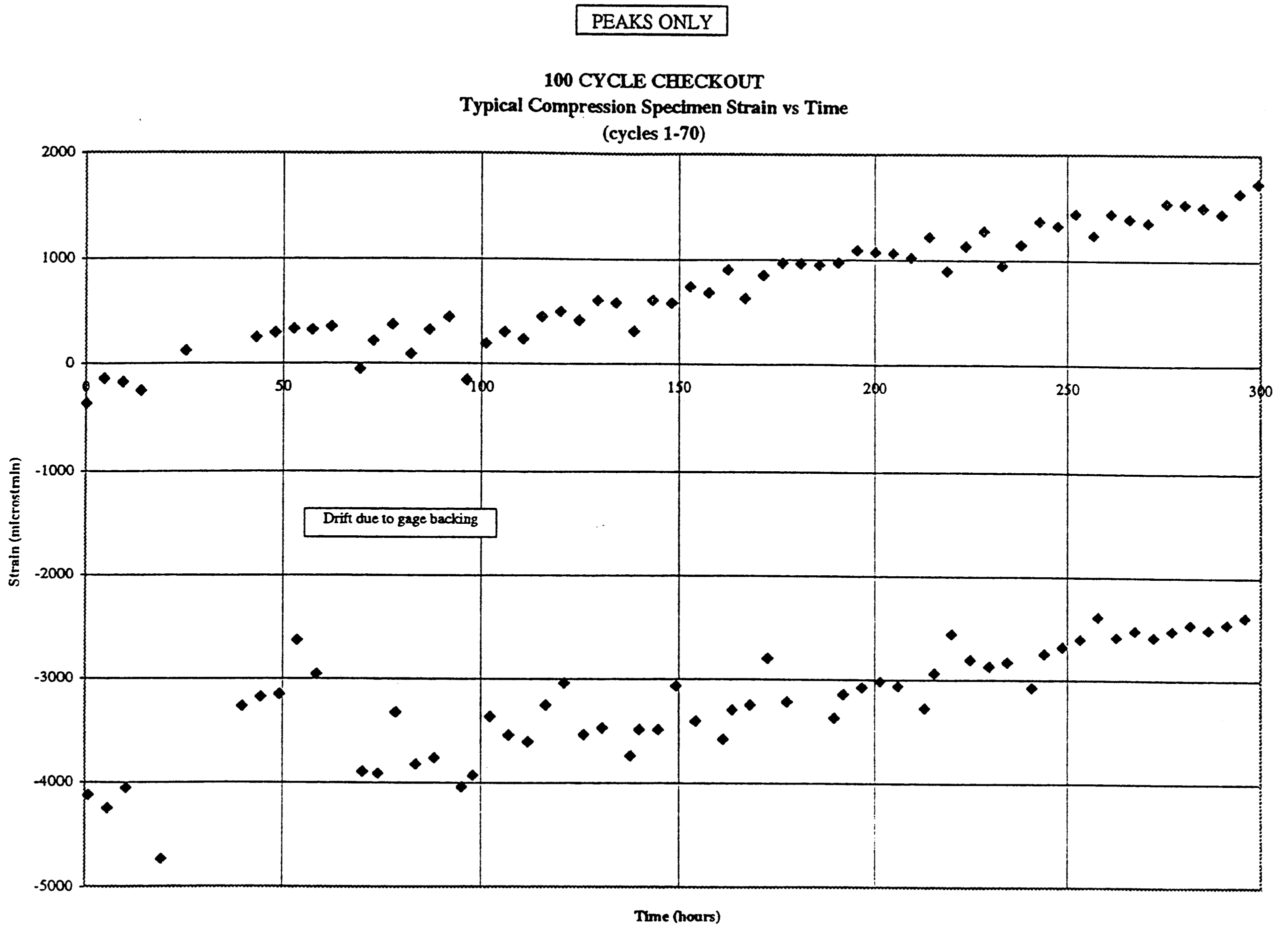


Figure 8.3-3. Compression Strain Profile (Cycles 1 to 70)

It was discovered that constantan gages have a documented increasing drift with high-temperature exposure. New gages with a Karma backing, which is impervious to long-term temperature exposure, were evaluated. A composite specimen was gaged with the new gage and with the constantan gage (control), placed in a constant-temperature 350°F oven for 10 days, and monitored daily. No drift was observed with the new gage, but the constantan gage drifted in a similar manner to the 100-cycle test. Based on these results, the new gage with the Karma backing was recommended for future testing. The strain gage manufacturer's name and model number of the new gages (for PMC specimens), as well as gages recommended for other specimen or fixture material, are given in figure 8.3-4.

Specimen/Fixture Material	Gage Manufacturer	Gage Model No.
PMC	Measurements Group	WK-00-250BG-350
Invar	Measurements Group	WK-00-250BG-350
Stainless Steel	BLH Electronics	FSM-12-35-S9
Titanium	BLH Electronics	FSM-12-35-S5

Figure 8.3-4. Thermal Cycling Strain Gages

Thermal cycle temperature profiles were generated for the 100-cycle test. Cycles from the beginning, middle, and end of the 100 cycles are shown in figure 8.3-5.

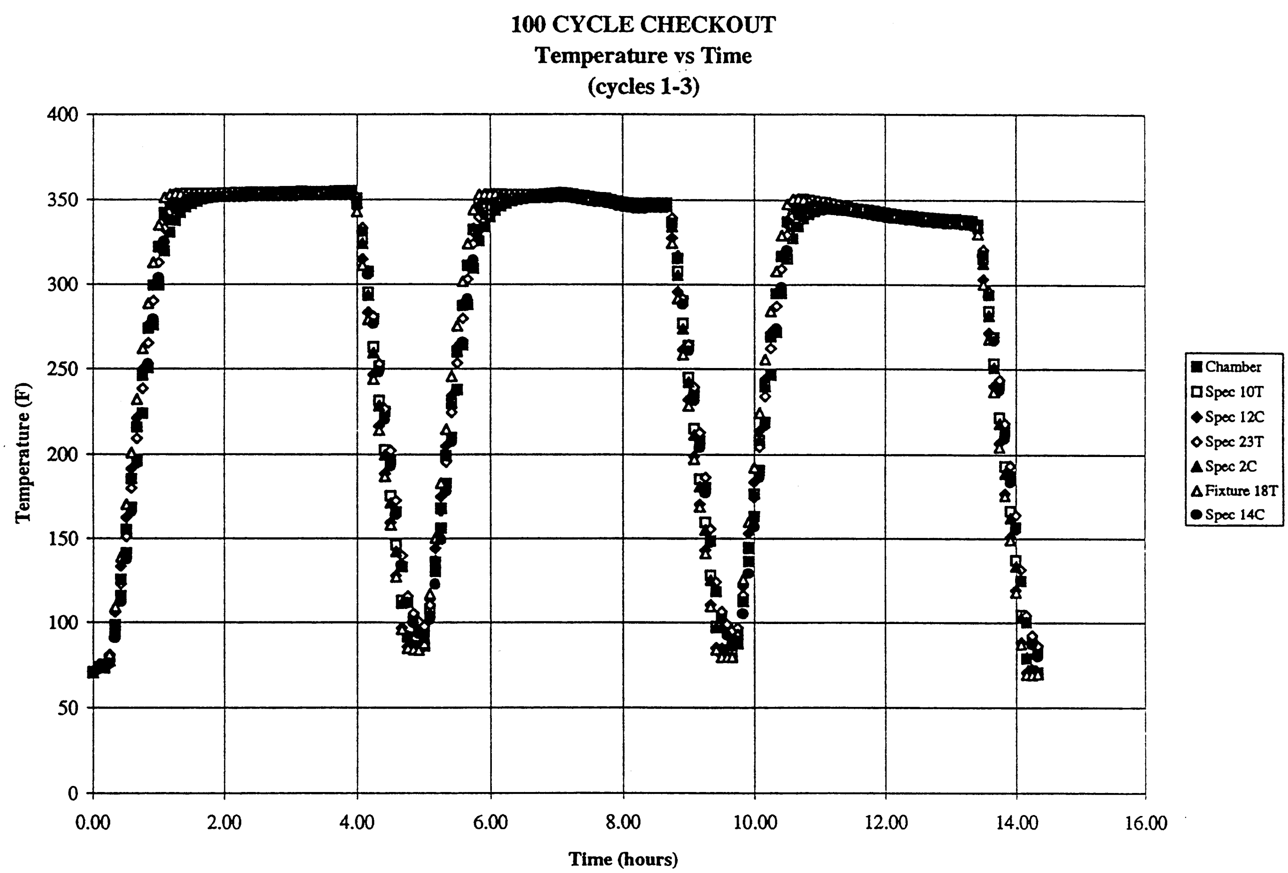


Figure 8.3-5. Thermal Cycling Temperature Profile

8.3.2 Chamber No. 3 Hydraulic Spectrum and Load Equivalence Test

A hydraulic spectrum was run with the goal of providing strains between -1,000 and 3,500 microstrain at a maximum frequency of 1 Hertz. This test demonstrated the load capabilities of the hydraulics, including a 1 Hertz load spike. Figure 8.3.2-1 shows the results of this test.

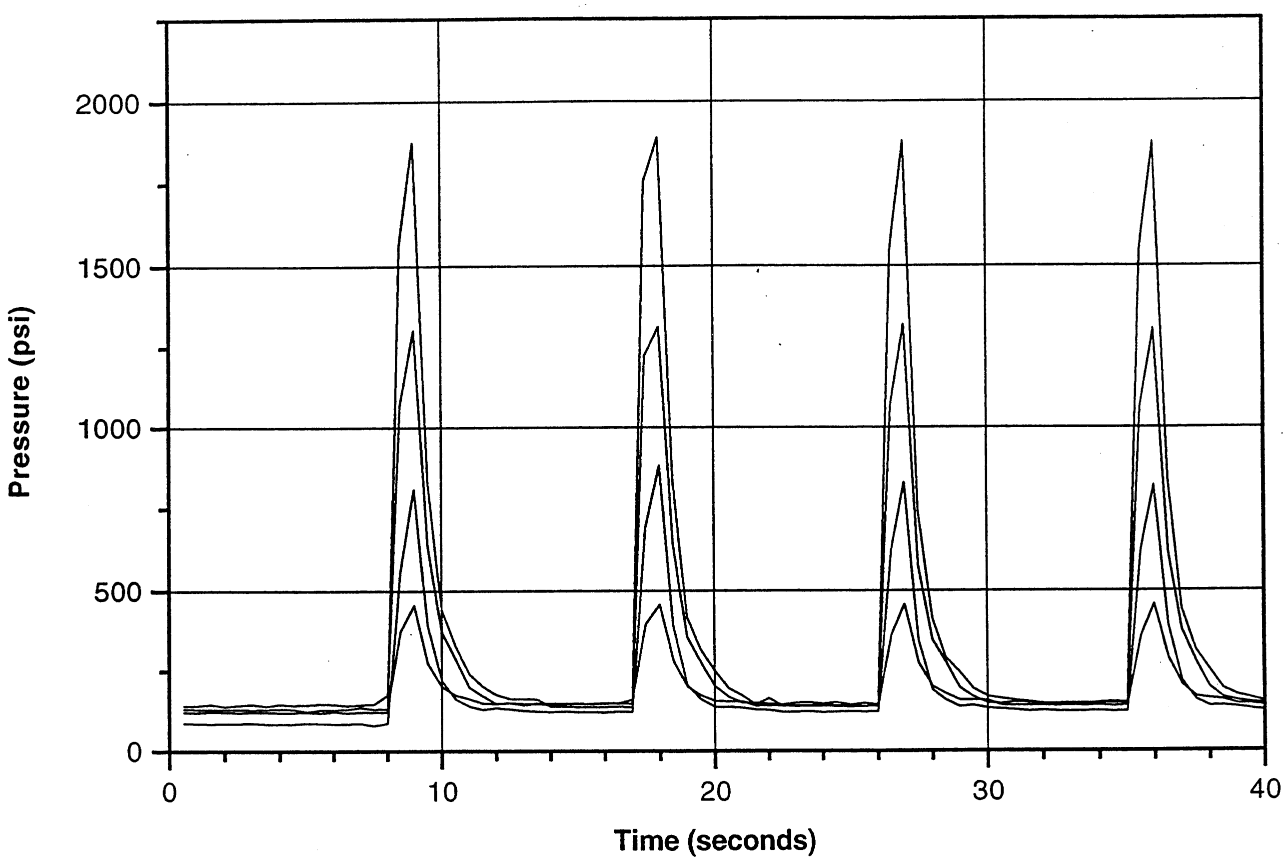


Figure 8.3.3-1 Hydraulic Spectrum Test Results

A hydraulic load cycle was also run to mimick the thermal load cycle used with the TAT and TAC fixtures. The hydraulics were run at room temperature using the setup described in section 5.1. Titanium dummy specimens were loaded to 750 lb (zone 4), 1500 (zone 3), 2250 (zone 2), 3000 (zone 1). The results of this test are given in figure 8.3.2-2.

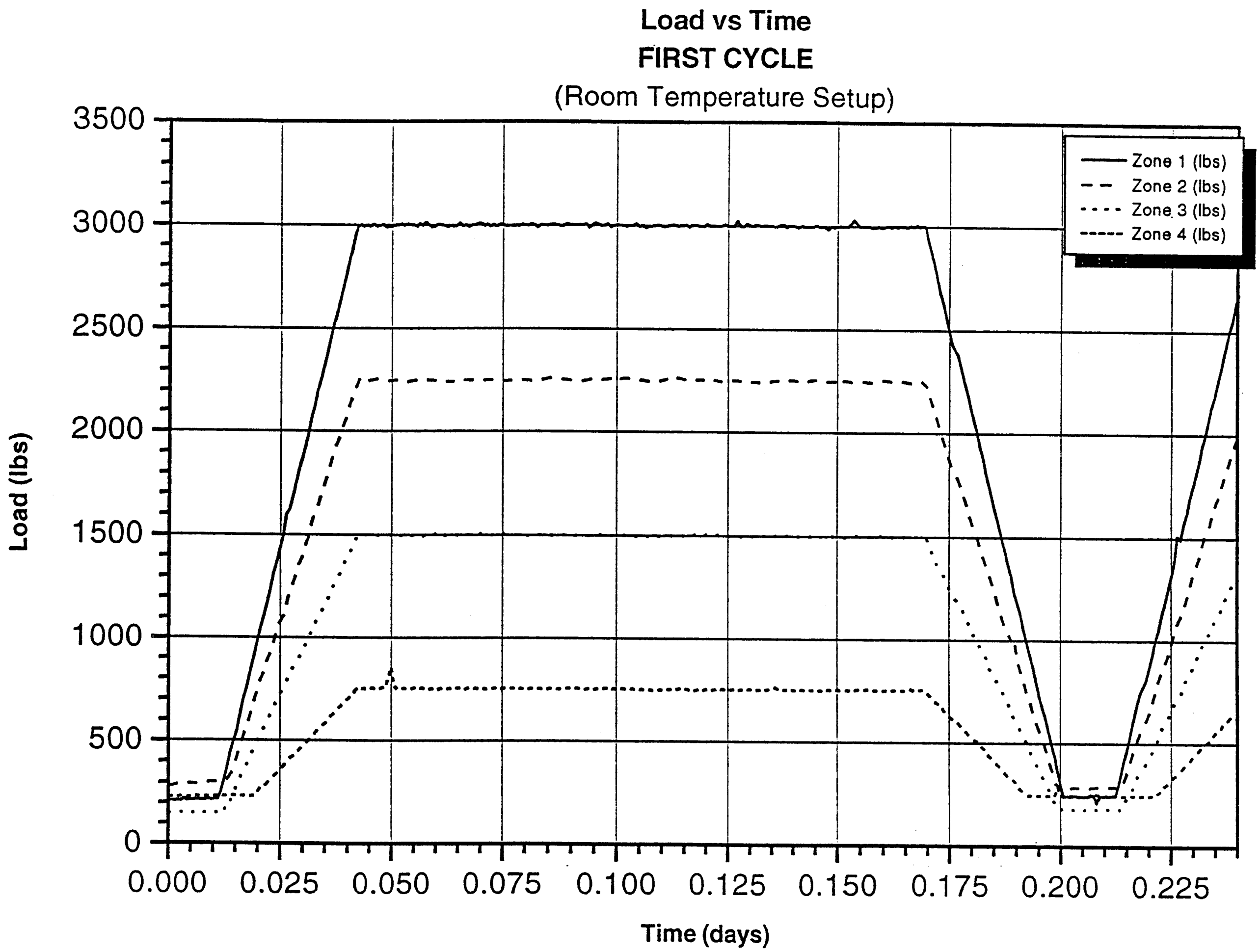


Figure 8.3.3-2 Load Equivalence Test Results

9.0 DURABILITY TEST PLAN

9.1 PLAN FOR 1,000-THERMAL-CYCLE TEST

An initial durability test plan has been formulated. Compression and tension specimens will be cycled in chamber Nos. 1 (300°F) and 2 (350°F). The thermal cycle profile was presented in figure 4.4.1-2. After thermal cycling, specimens will be tested to failure to obtain residual strength data. The planned test matrix is shown in figure 9.1-1.

Load Type	Material	Exposure Temp (°F)	Maximum Strain	Prestrain	# Specimens	# Gages on Specimen	# Gages on Fixture
Tension	K3B/IM7	Room Temp	Failure (Baseline)	0	5		
		300	0	0	2		
				0.006	2		
			0.002	0	2	2	2
				0.006	2	2	2
			0.004	0	2	2	2
				0.006	2	2	2
		350	0	0	2		
				0.006	2		
			0.002	0	2	2	2
				0.006	2	2	2
			0.004	0	2	2	2
				0.006	2	2	2
	PETI/IM7	350	0	0	2		
				0.006	2		
			0.002	0	2	2	2
				0.006	2	2	2
			0.004	0	2	2	2
				0.006	2	2	2
Compression	K3B/IM7	Room Temp	Failure (Baseline)	0	5		
		300	0	0	2		
				0.006	2		
			0.002	0	2	4	2
				0.006	2	4	2
			0.004	0	2	4	2
				0.006	2	4	2
		350	0	0	2		
				0.006	2		
			0.002	0	2	4	2
				0.006	2	4	2
			0.004	0	2	4	2
				0.006	2	4	2

Figure 9.1-1. Matrix for 1,000-Thermal-Cycle Test

9.2 TEST SPECIMENS AND INSTRUMENTATION

Both K3B/IM7 and PETI/IM7 specimens will be tested during the first 1,000 cycles. K3B/IM7 laminates have been fabricated by Boeing Materials Technology Laboratories and PETI/IM7 laminates are currently being fabricated by Northrop. (The K3B laminate cure cycle is contained in appendix A.)

A 16-ply quasi-isotropic layup, $(45/\text{-}45/0/90)_{2S}$, was used for the tension laminates, and a 32-ply quasi-isotropic layup, $(45/\text{-}45/0/90)_{4S}$, was used for the compression laminates. Tension and compression specimen configurations were shown in figure 8.3-1. The high-temperature strain gages discussed in section 8.3 will be used on all the test specimens. Gages will also be attached to unloaded dummy specimens to determine temperature strain effects. These data will be used to calibrate the test specimen gages. Thermocouples will be attached to some of the tension and compression specimens to monitor specimen heatup rate and soak times.

9.3 BASELINE TEST RESULTS FOR K3B/IM7

Baseline testing was performed as outlined in figure 9.1-1. All specimens were tested at room temperature. Compression specimens were tested using a Northrop 3- by 1-in face-supported fixture. Specimens were originally tested in accordance with ASTM D695, except without tabs, but end-brooming failures occurred. Baseline test results are shown in figure 9.3-1.

Test Type	**Specimen ID**	**Ultimate Stress (ksi)**	**Chord [1] Modulus (msi)**
Tension	BC144-T-1	124.2	8.58
	BC144-T-2	132.0	8.80
	BC144-T-3	135.2	8.70
	BC144-T-4	130.2	8.45
	BC144-T-5	134.3	8.53
		average = 131.2 std. dev. = 3.9	**average = 8.61** std. dev. = 0.12
Compression	IT26-C-1	109.0	7.79
	IT26-C-2	103.8	7.60 [2]
	IT26-C-3	105.2	7.80
	IT26-C-4	108.6	7.76
	IT26-C-5	110.0	7.90
		average = 107.3 std. dev. = 2.4	**average = 7.77** std. dev. = 0.10

Notes:
1. Chord modulus calculated at: 3,000 and 6,000 microstrain for tension
1,000 and 3,000 microstrain for compression.
2. End failure; specimen too lightly tightened.

Figure 9.3-1. Baseline Test Results for K3B/IM7

10.0 CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

The conclusions are as follows:

a. The current tension and compression fixtures were capable of providing the designed strains of approximately 4,000 microstrain, using a temperature variation of 280°F. Test results gave agreement to predicted strains within 1% in both cases.

b. Alignment ability and torsional stability of the original compression fixture were inadequate; however, they were improved greatly with minor redesign.

c. The currently projected price (for large quantities) of DiCTE fixtures compares favorably with the use of hydraulic load frames; however, tension and reverse load fixtures are still expensive. Much of this expense is due to the wedge grips.

d. With current instrumentation, it is difficult to differentiate the viscoelastic response of the material being tested from the potential settling of the fixture components.

e. DiCTE fixtures are capable of providing limited designed-in phasing differences and spikes; however, they are not adequate for spectrum testing.

f. The current compression fixture, thermal cycle, and specimen system appears to relax maximum compressive strains applied to the specimen at a significant rate of approximately 2 microstrain per cycle, after the specimen and fixture have seated (the first 70 to 100 hr of cycling). The resulting calibration intervals (<1 month) are still considered acceptable, assuming the fixtures can be adjusted outside the oven environment.

g. Although DiCTE fixtures are capable of providing constant strain in an isothermal environment, simpler (more cost-effective) approaches are available.

h. Fixtures, specimen configurations, and measuring devices have proved basically sound; however, their long-term reliability is still unproved.

i. Advantages and disadvantages versus the standard (hydraulic) approach are not currently well understood.

j. Oven sizes, fixture thermal mass, and cycle parameters (minimum temperature, heating and cooling rates, etc.) appear to significantly affect the cost of performing thermal cycling. Liquid nitrogen is a major contributor.

k. DiCTE fixtures must be thermally optimized for heat transfer to eliminate any lags in phasing and small strain irregularities at the end of each cycle and to ensure usefulness to thermal profiles not containing significant hold times.

l. The analysis methodologies and resulting analysis tools performed well for both analyzing and optimizing fixtures. Analytical results and test data matched to within 1% for strain values.

m. Nitinol-driven fixtures may have great potential; however, significant efforts in design and material development would be required.

10.2 RECOMMENDATIONS

The recommendations are as follows:

a. Perform detailed cost breakdown of current fixtures, and focus fixture redesign efforts by investigating alternatives for high-cost parts (e.g., grips).

b. Include testing of a reference material that is "creep free" for our exposure scenarios in the 100-cycle checkout of each fixture, and use in subsequent testing if fixture settling is significant. This will allow differentiation of specimen creep and fixture settling effects.

c. Investigate use of high-temperature extensometers, LVDTs, and instrumented drivers to fully assess load and displacement behavior of the fixture and specimen. These instrumentation alternatives may provide a low-cost method for periodic fixture calibration. Instrumenting the steel driver also may provide a load measurement that can be used to calibrate the fixtures.

d. Begin longer term (4,000-hr) testing on all DiCTE fixtures to obtain initial cyclic viscoelastic response and residual strength data on candidate systems, to verify fixture calibration interval, and to expose weak system elements that must be altered to ensure long-term test reliability.

e. Conduct baseline and aged property testing, including residual strength, stiffness, photomicroscopy, and chemical and physical analysis to determine the extent and mechanisms of material degradation after thermal and mechanical loading.

f. Perform initial durability testing (sec. 9.0 test plan) to verify test equipment and obtain residual strength data.

g. Test other HSCT candidate composite materials as they become available.

11.0 REFERENCES

1. Wishart, Rod, and Coxon, Brian, "Design and Testing of a Thermally Actuated Compression Fixture Final Report," Intec Report #BC0107, Bothell, WA, 1993.

2. Wishart, Rod, and Coxon, Brian, "100 Thermally Actuated Compression Cycles Final Report," Intec Report #BC0112, Bothell, WA, 1994.

3. Wishart, Rod, and Coxon, Brian, "Design and Testing of a Thermally Actuated Tension Fixture Final Report," Intec Report #BC0113, Bothell, WA, 1994.

4. Thompson, Darren J., "Load Measurement and Adjustment of Thermally Actuated Fixtures," Intec Report #BC0137, Bothell, WA, 1994.

5. Engineering Data Sheet "WK-Series Strain Gage General Information Sheet," Gage type WK-00-125BB-350, Batch Q78094, S-T-C data curve, Measurements Group, Inc., Raleigh, NC.

APPENDIX A - LAMINATE CURE CYCLES

K3B Cure Cycle (Autoclave)

a. Apply 5 inHg.
b. Heat up at 1°F/min.
c. Apply full vacuum (30 inHg) when part reaches 350°F.
d. Apply 185 psi when part reaches 655°F.
e. Dwell at 655°F for 1 hr.
f. Cool part to 450°F at 1°F/min.
g. Cool from 450°F to room temperature at 5°F/min.
h. Release pressure and debag.

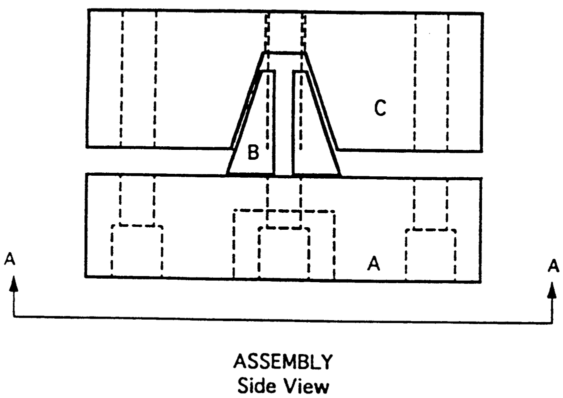
BMI Cure Cycle (Autoclave)

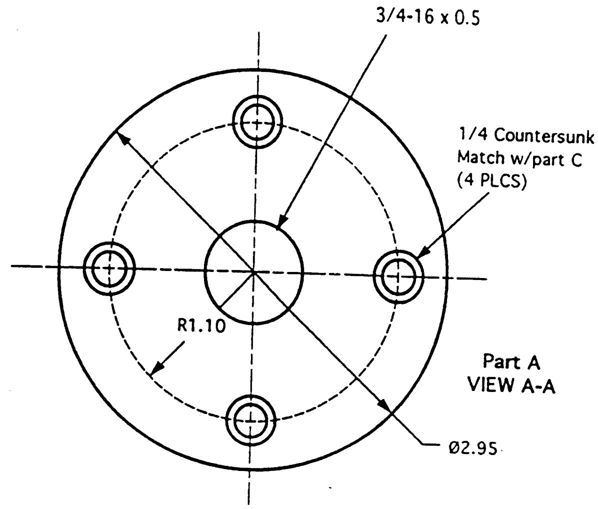
a. Apply 22 inHg vacuum, minimum.
b. Heat to 300°F at 3°F/min.
c. Dwell at 300°F for 30 min.
d. Vent bag and apply 85 psig.
e. Heat to 375°F at 3°F/min.
f. Dwell at 375°F for 4 hr.
g. Cool to 120°F at $<$5°F/min before releasing pressure.
h. Debag.

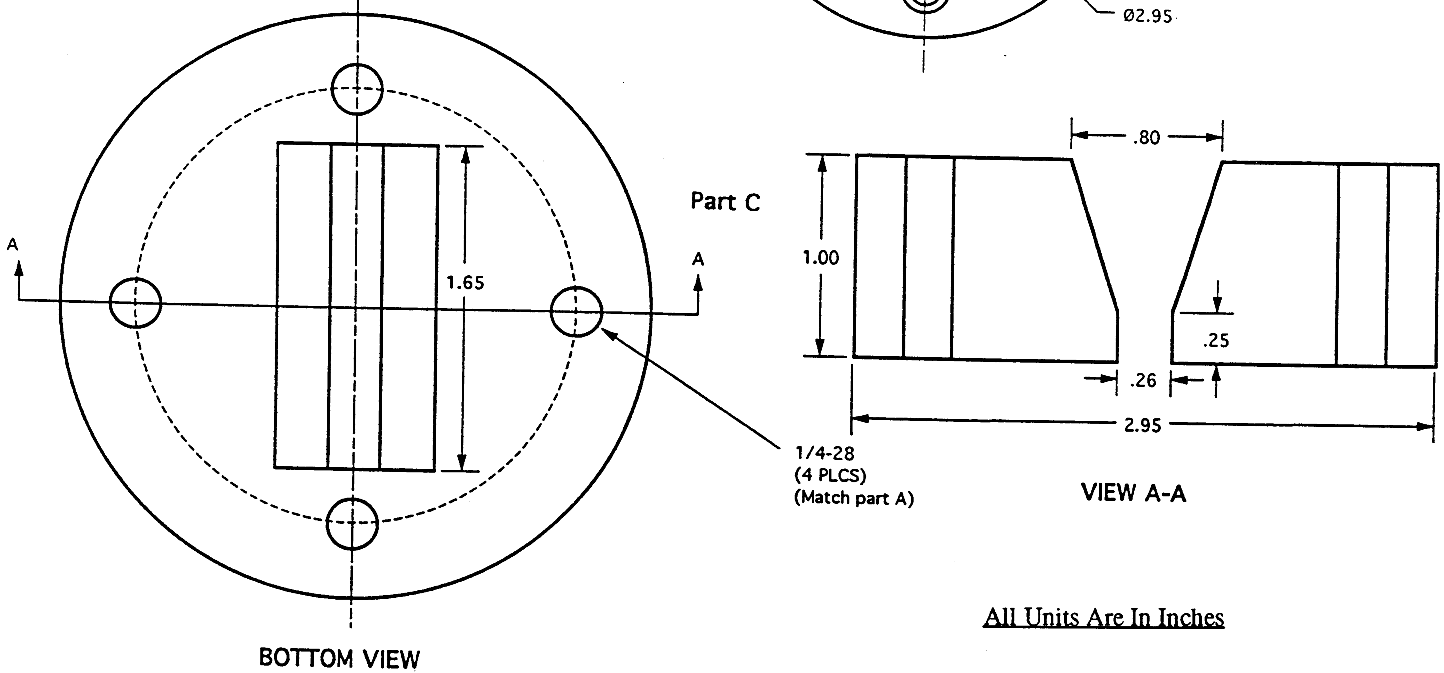
BMI Post Cure (Freestanding in Oven

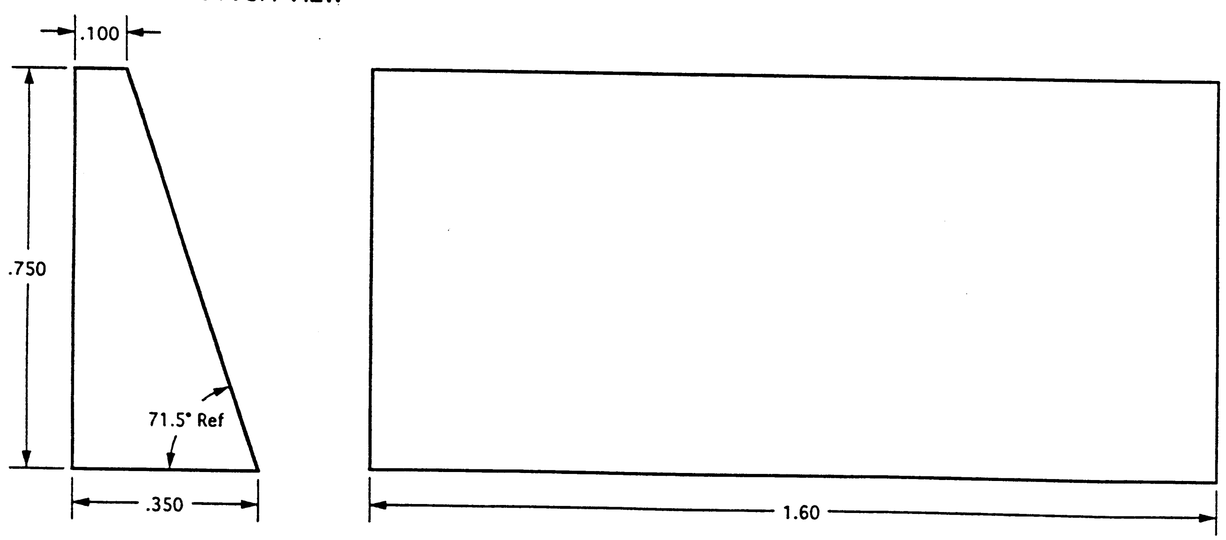
i. Heat to 420°F at 5°F/min.
j. Dwell at 420°F for 6 hr.
k. Cool to 120°F at $\leq$5°F/min.

APPENDIX B - WEDGE GRIP DETAILED DRAWINGS

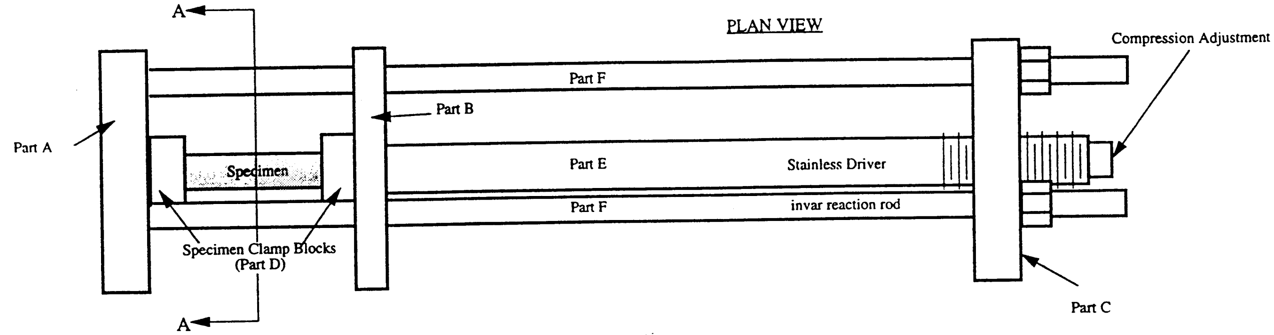


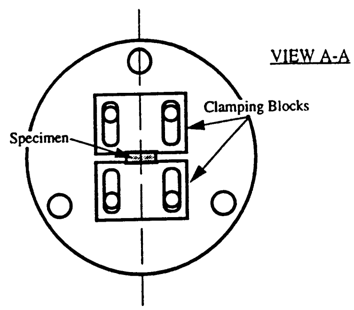






APPENDIX C - COMPRESSION FIXTURE DETAILED DRAWINGS



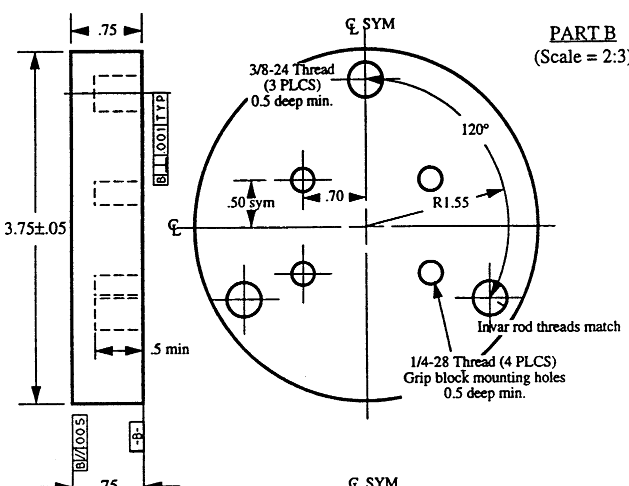


PRINCIPLE OF OPERATION

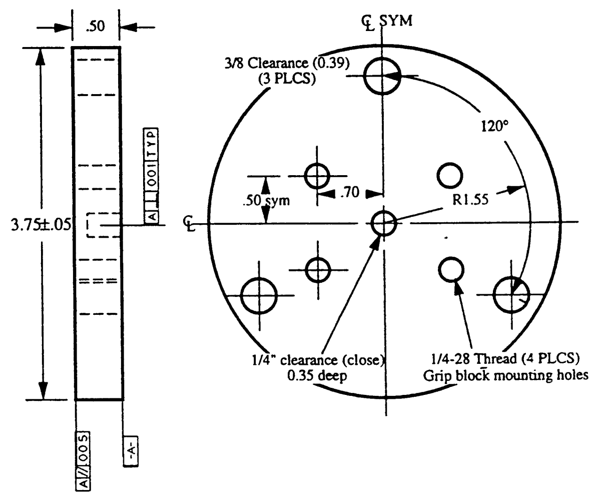
Three invar rods (Part F) are threaded into Part A, and Parts B and C slide along the rods. Part C is located using nuts threaded onto the invar rods. Part E, the driver, is butted against Part B, and threaded into part C. As the assembly is heated, the stainless steel of Part E expands approximately 9 times farther than the invar rods, thereby providing a compressive load to the specimen, which is held in place between Parts A and B by the clamping blocks of Part D.

PART A
(Scale = 2:3)

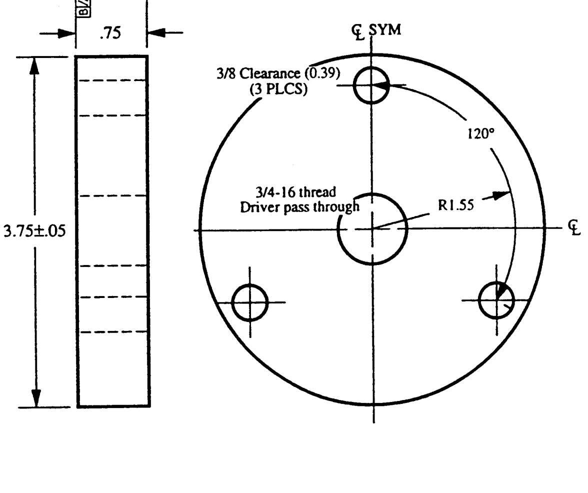
Side View



PART B
(Scale = 2:3)



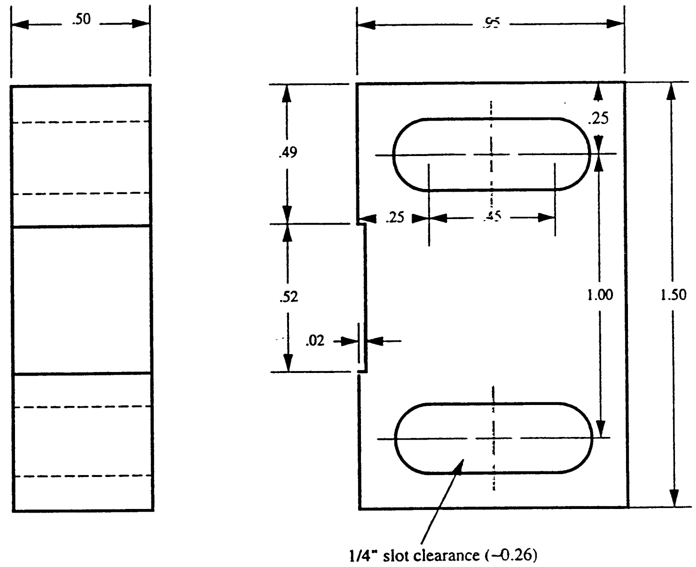
PART C
(Scale = 2:3)



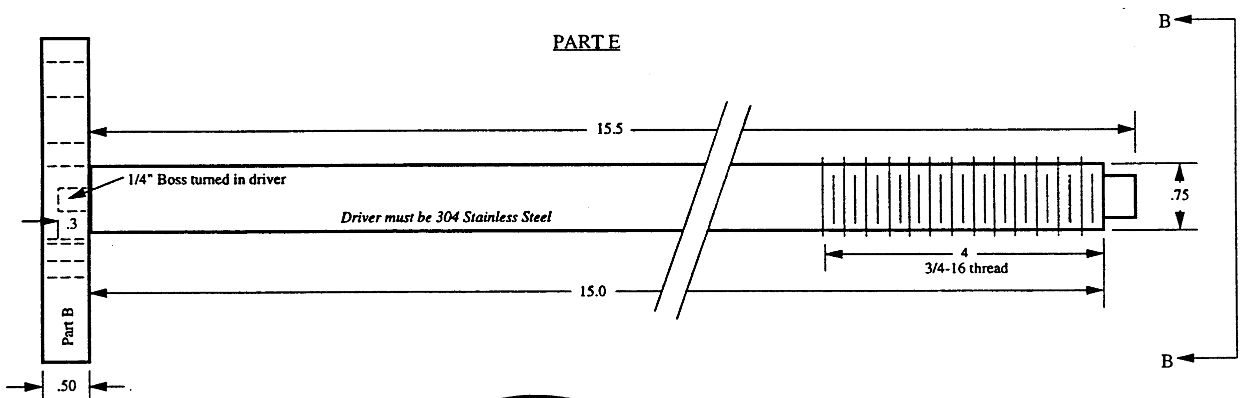
3/8" hole positions are identical for parts A, B, and C
(A is threaded, B and C are clearance)

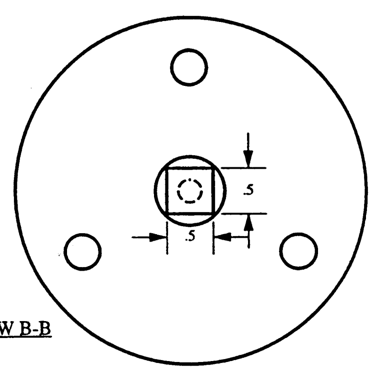
All Units Are In Inches

Part D



PART E

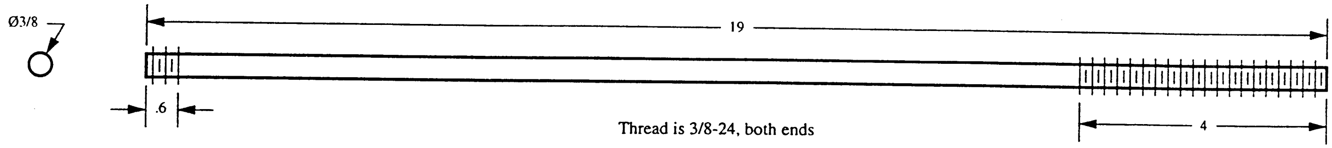




VIEW B-B

All Units Are In Inches

Part F



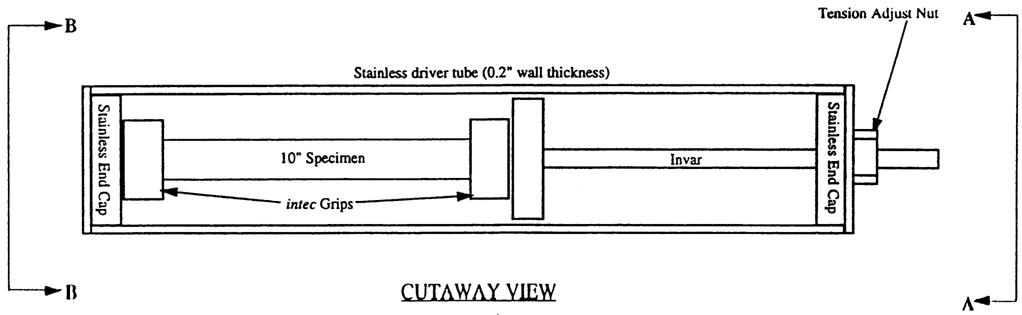
All Units Are In Inches

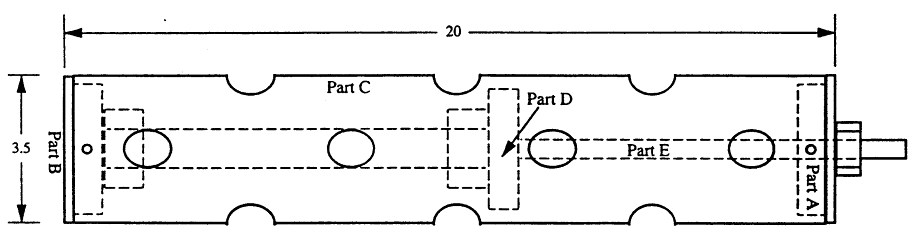
HSCT End Loaded Compression Fixture Notes

- The driver (Part E) must be manufactured from 304 stainless steel.
- Other parts marked "Stainless" may be manufactured from any stainless steel.
- The reaction rods (Parts F) are invar 36.

Part Number	Part Type	Part Description	Number Required per Assembly
A	End Support	Loads outside end of specimen	1
B	Center Support	Loads inside end of specimen	1
C	Reaction Plate	Reacts load of driver. Provides compression load adjustment	1
D	Specimen Grip Blocks	Grip specimen ends	4
E	Driver	Expands with temperature to give compression load	1
F	Reaction Rod	React compression load	3

APPENDIX D - TENSION FIXTURE DETAILED DRAWINGS

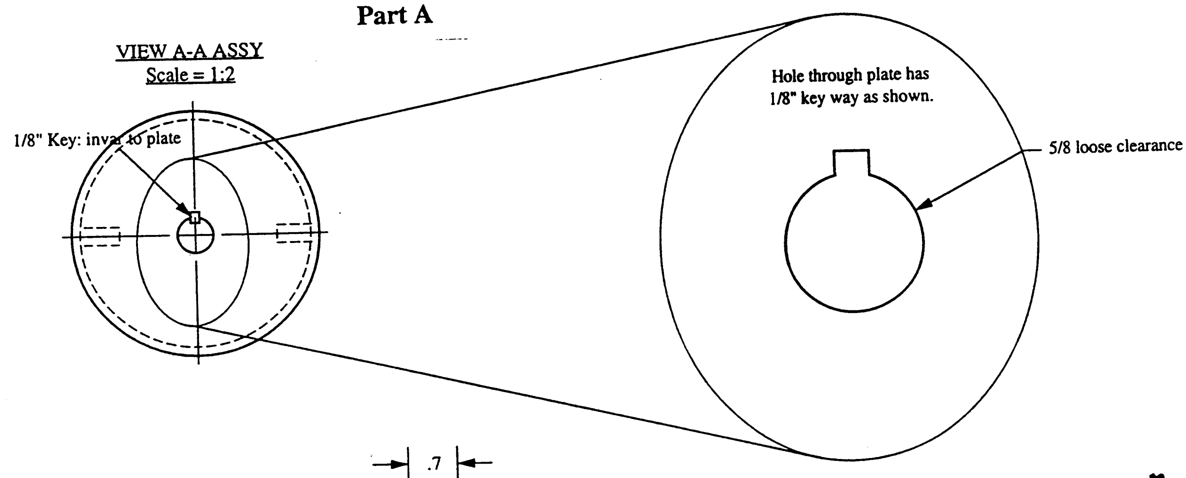


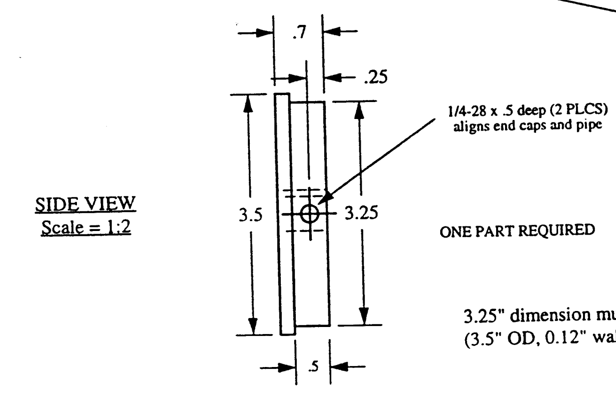


Cutouts allow heat transfer to specimen

PRINCIPLE OF OPERATION
A test specimen is mounted in a set of grips, which mount to Parts D and B. Part E is constructed of invar steel, which is a low thermal expansion steel. Part E is mounted to Part D, and is restrained by a nut against Part A. As Part C expands with increasing temperature at a rate of about 9 times that of the invar and the specimen, a tensile load is applied to the specimen in-phase with rising temperature. This fixture will be placed in a thermally cycling chamber for up to 7 years to apply cyclic tensile loads to graphite specimens. (Note that the grip assemblies are not included in these drawings.)

Part A



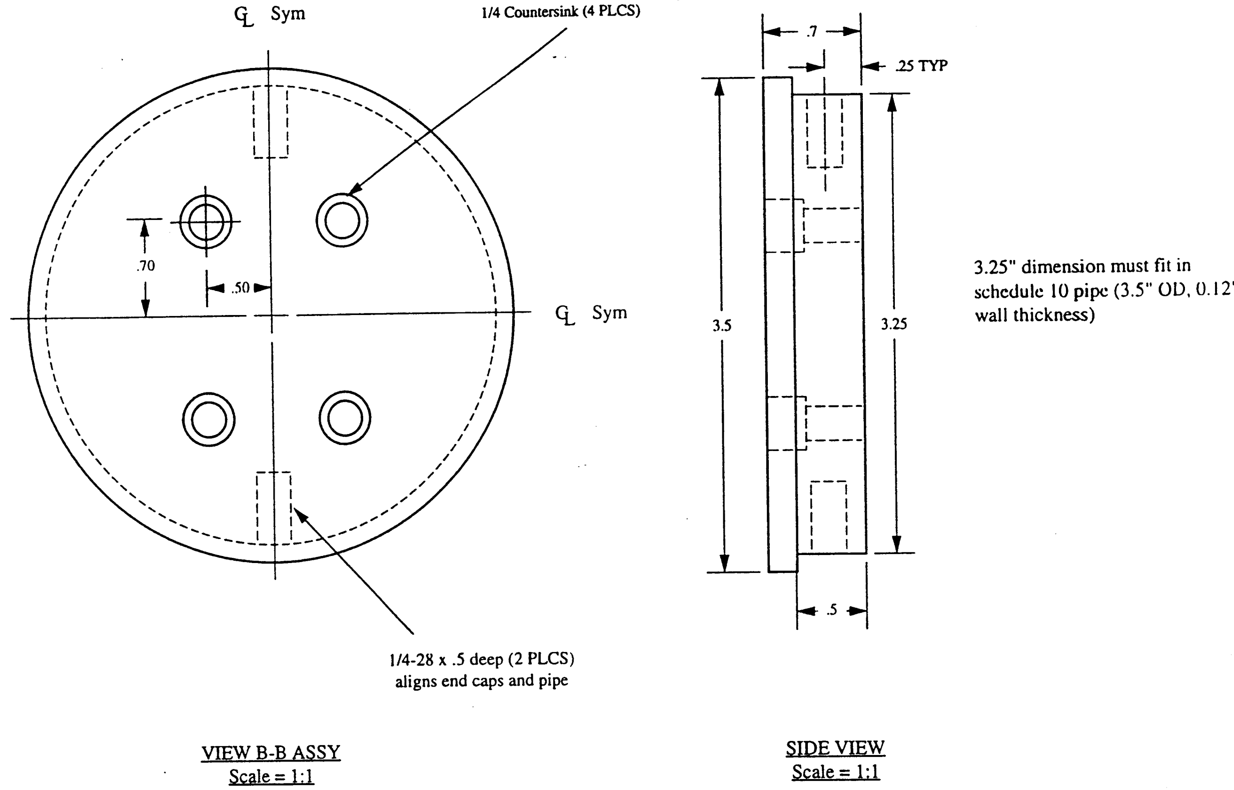


All Units Are In Inches

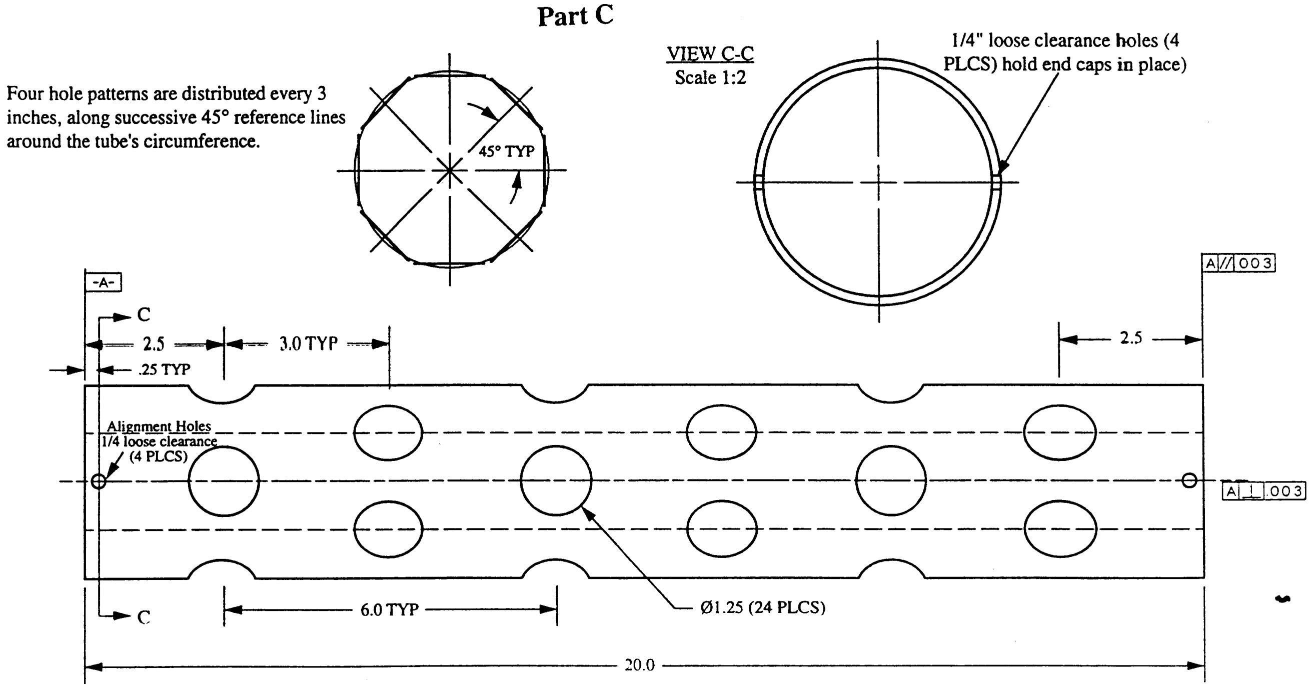
ONE PART REQUIRED

3.25" dimension must fit in schedule 10 pipe
(3.5" OD, 0.12" wall thickness)

Part B



Part C

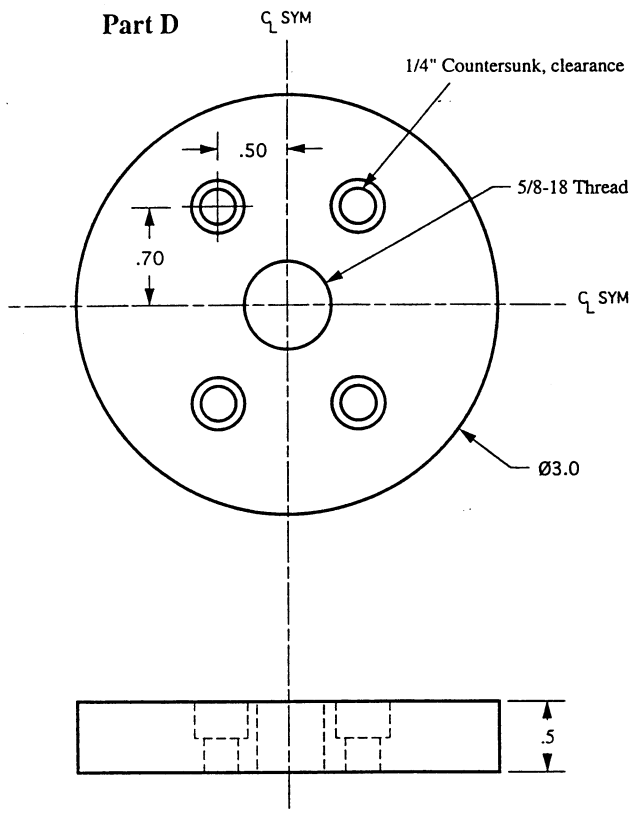


All Units Are In Inches

Pipe is schedule 10 (3.5" OD with 0.12" wall thickness)

Cutouts allow heat transfer to specimen

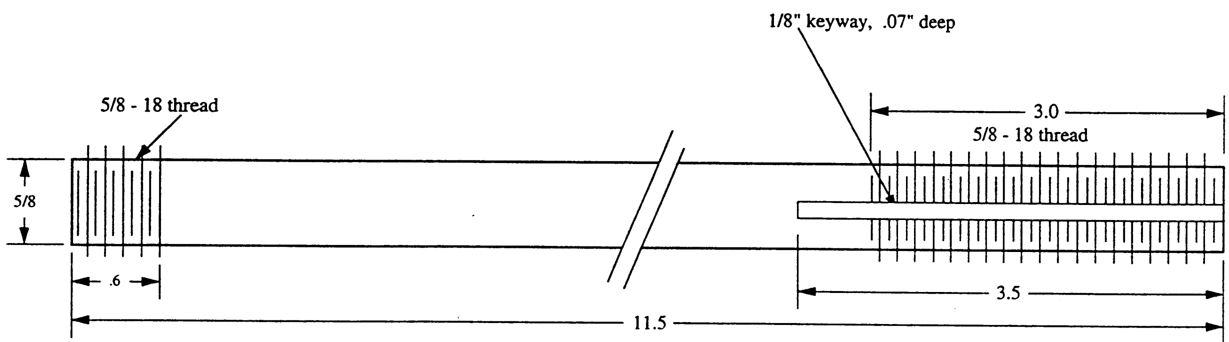
Part D



BOTTOM VIEW

ONE PART REQUIRED

Part E



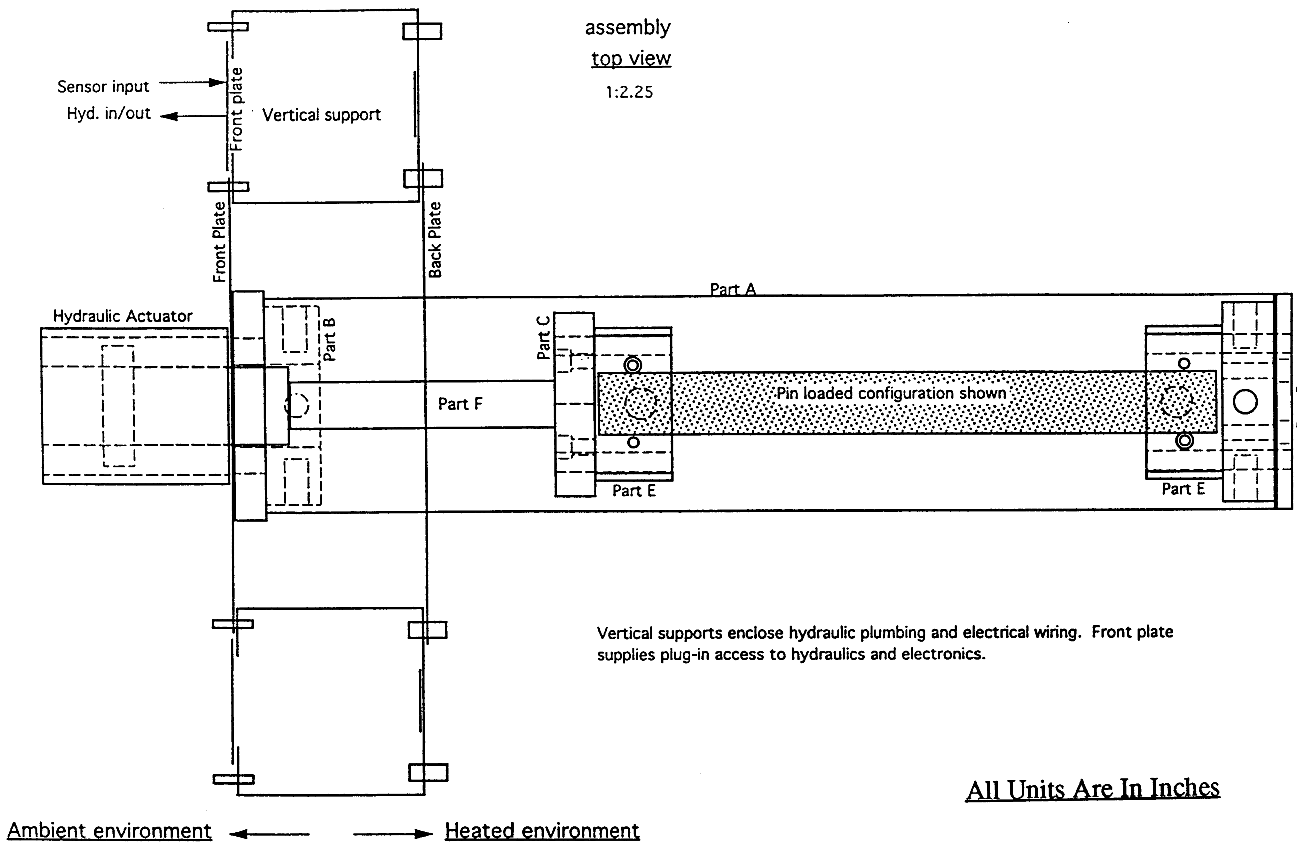
All Units Are In Inches

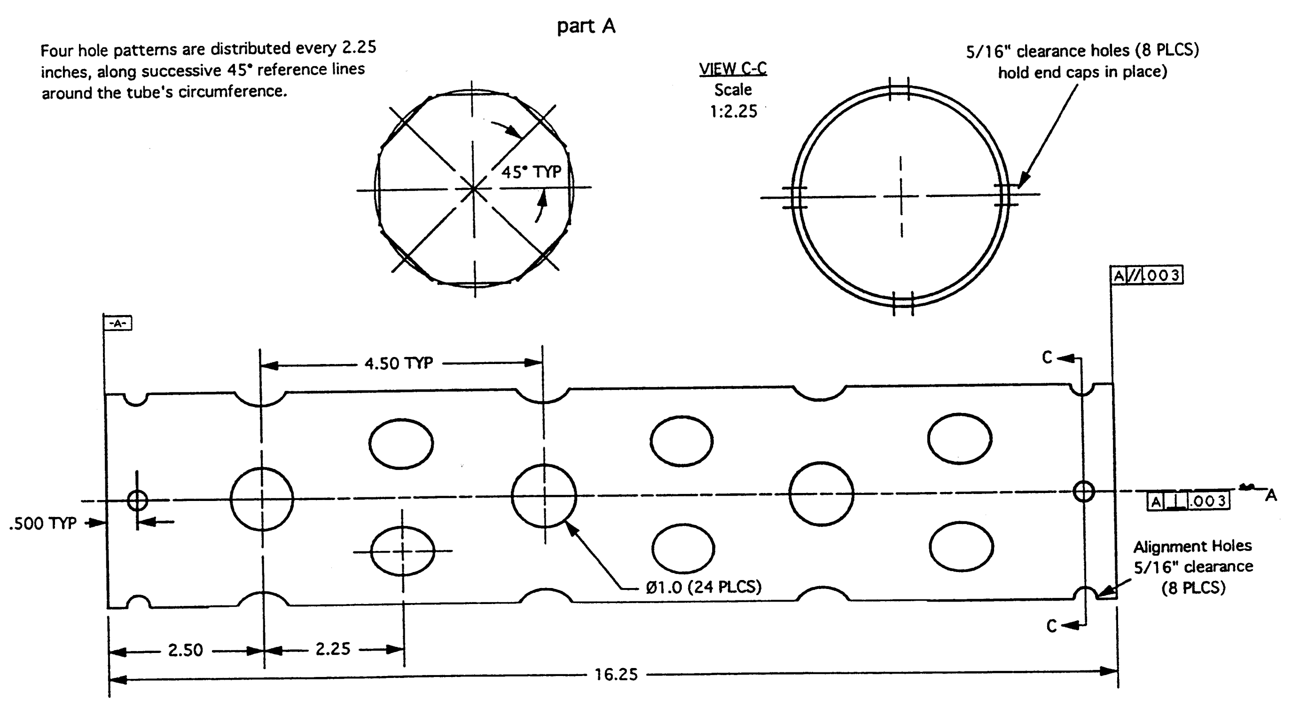
HSCT Tension Fixture (Gripped Specimen) Manufacturing Notes

•Please quote quantities of 1, 33, and 1000.
•All parts called as "stainless" may be any stainless steel. Pipe must be 304 stainless.
•Pipe is 3.5", schedule 10. OD = 3.5, wall thickness = 0.12".
•Construction of the first 33 fixtures must be complete by May 31. (One fixture built first for QC, followed by numbers 2 through 33.

Part Number	Part Type	Work Description	Number Required
A	End Cap	Cap reacts load from tension nut.	1
B	End Cap	End cap mounts specimen grip at outside end of pipe.	1
C	Driver Pipe	304 stainless, schedule 10 pipe	1
D	Grip Clamp Plate	Mounts grip assembly at middle of pipe.	1
E	Invar Rod	Reacts load from driver	1

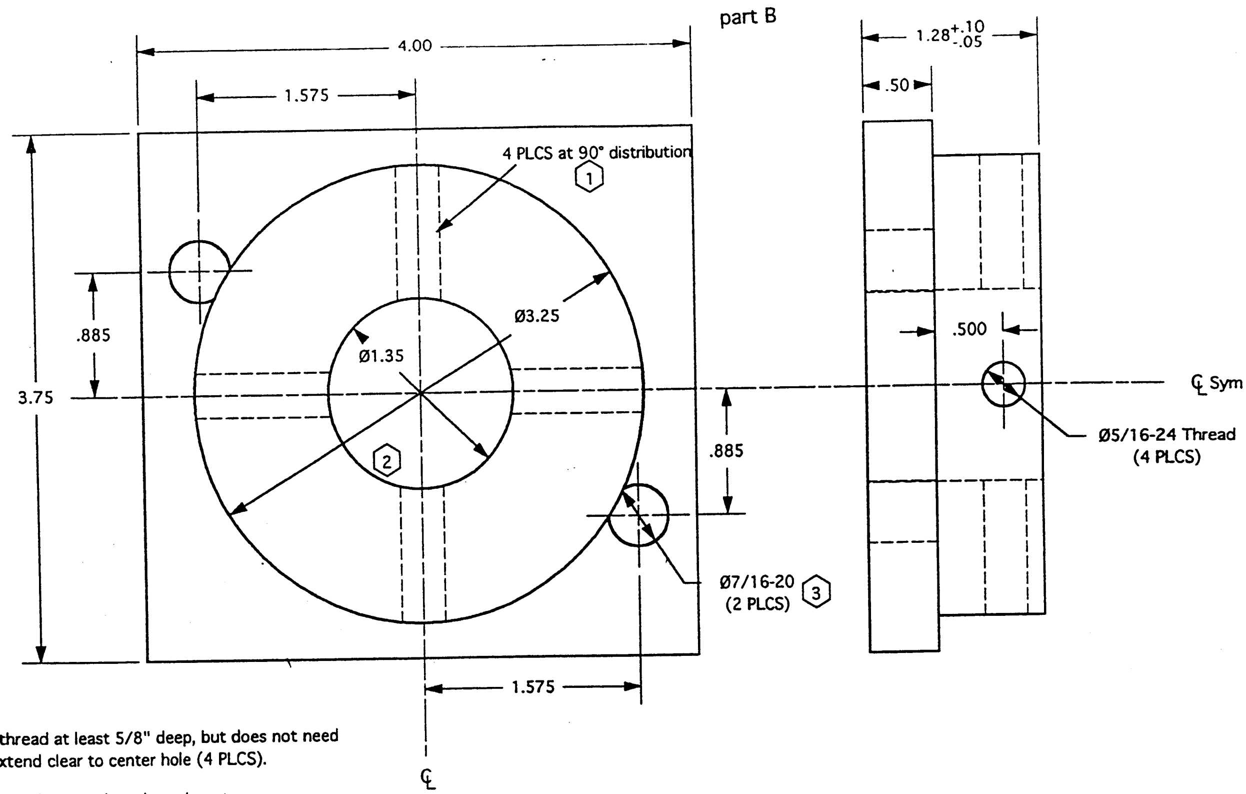
APPENDIX E - HYDRAULIC FIXTURE DETAILED DRAWINGS





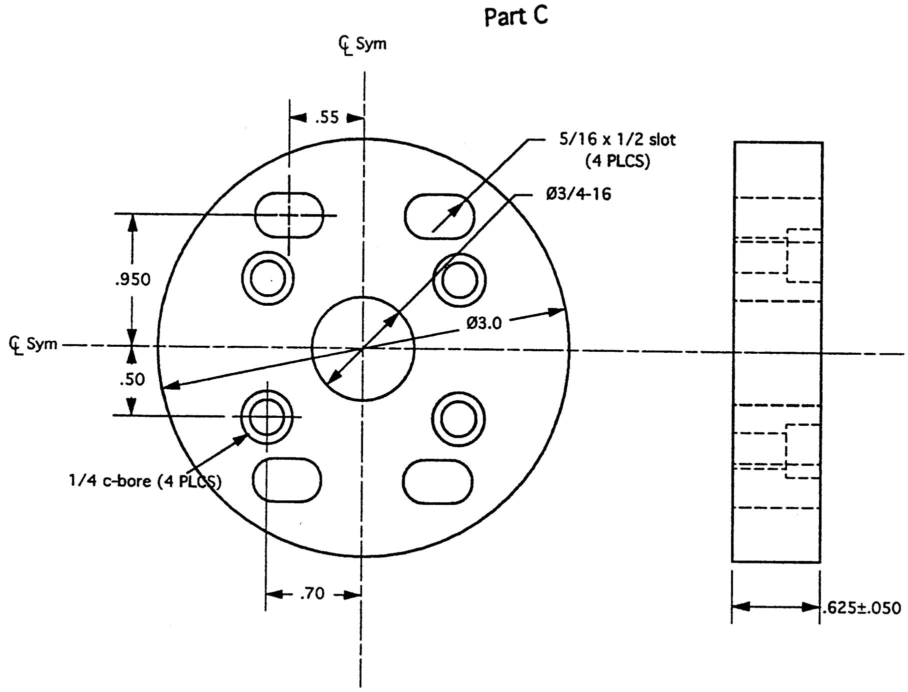
Pipe is schedule 10 (3.5" OD with 0.12" wall thickness)

Cutouts allow heat transfer to specimen



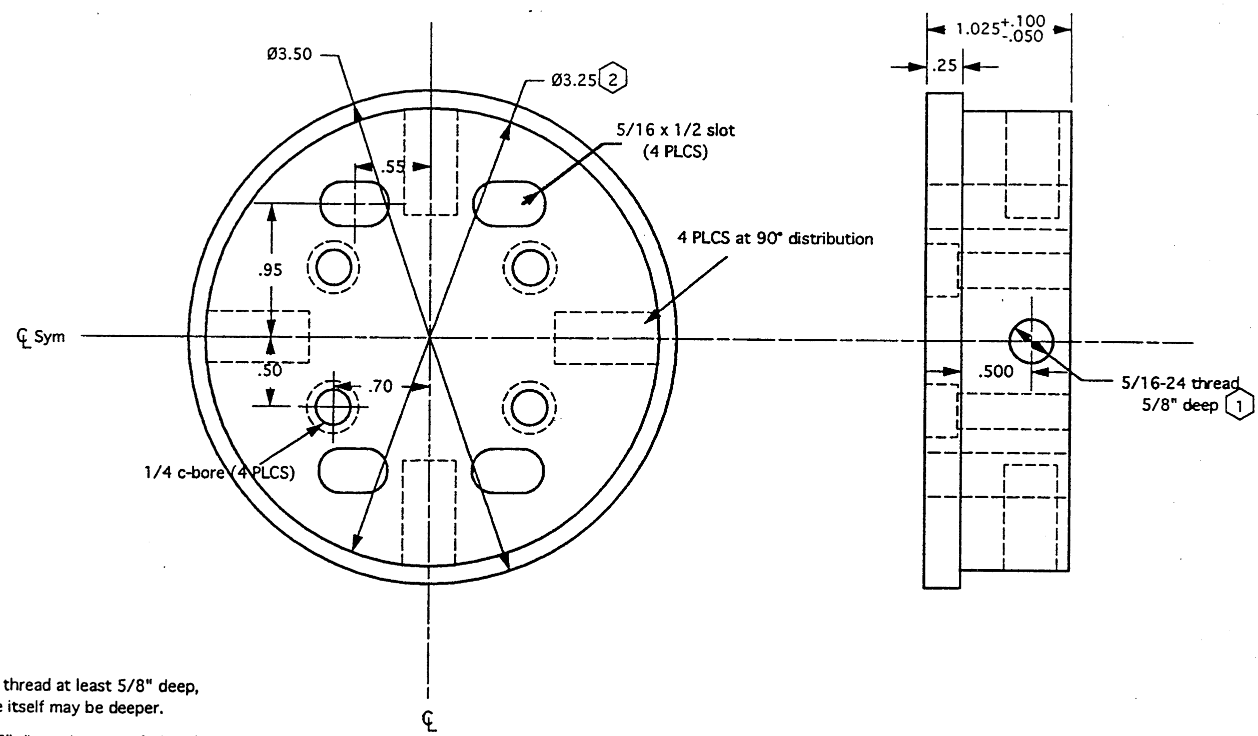
1. Cut thread at least 5/8" deep, but does not need to extend clear to center hole (4 PLCS).
2. 1.35" hole goes clear through part.
3. Thread extends through 0.5" flange. Slight cutting of 3.25" diameter is acceptable.

Part C



All Units Are In Inches

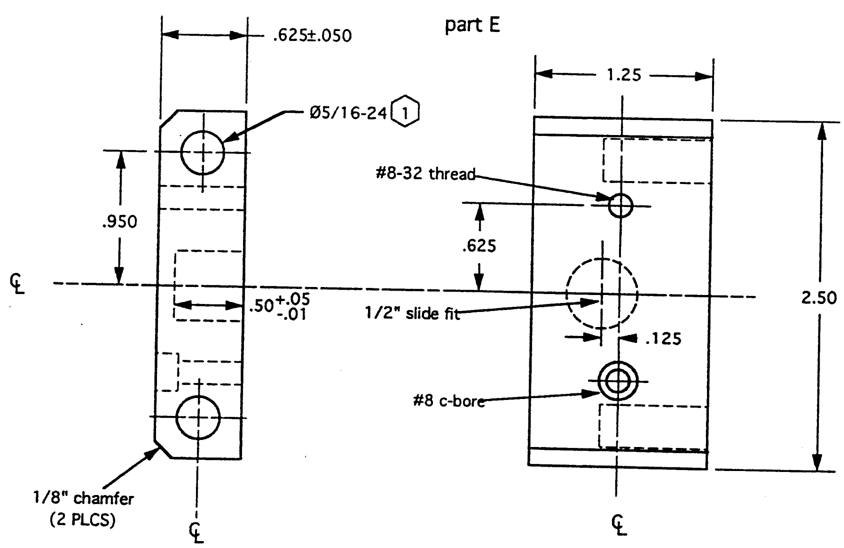
part D



(1) Cut thread at least 5/8" deep, hole itself may be deeper.

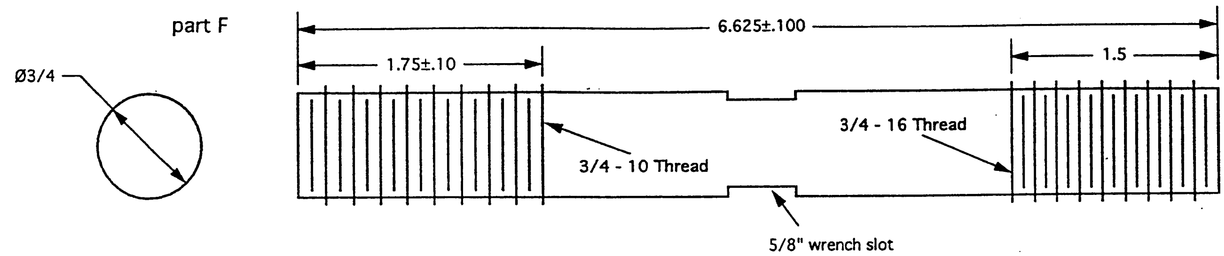
(2) 3.25" dimension must fit in schedule 10 pipe (3.5" OD, .12" wall)

part E



Material: 17-4 SS

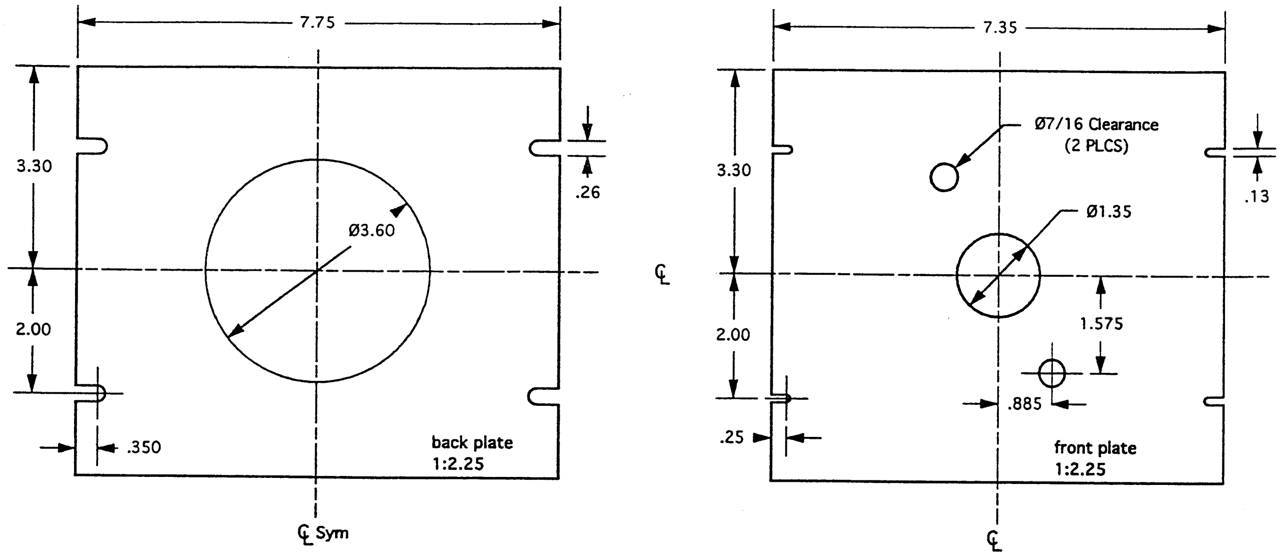
All Units Are In Inches



(1) 5/16 hole min. depth =0.75". Need not go clear through.

Material: 17-4 SS

front and back plates



Material is 16 gauge

<u>All Units Are In Inches</u>

PARTS LIST

Part	Description	Material	Quantity per Assy
A	Reaction Tube	6061 Aluminum	1
B	Cylinder Mount	17-4PH SS	1
C	Center Grip Plate	17-4PH SS	1
D	End Grip Plate	17-4PH SS	1
E	Pin Clamp	17-4PH SS	4
F	Loading Rod	17-4PH SS	1

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13. ABSTRACT ***(Maximum 200 words)***
This report covers a portion of an ongoing investigation of the durability of composites for the High Speed Civil Transport (HSCT) program. Candidate HSCT composites need to possess the high-temperature capability required for supersonic flight. This program was designed to initiate the design, analysis, fabrication, and testing of equipment intended for use in validating the long-term durability of materials for the HSCT. This equipment includes thermally actuated compression and tension fixtures, hydraulic-actuated reversible load fixtures, and thermal chambers. This equipment can be used for the durability evaluation of both composite and adhesive materials. Thermally actuated fixtures are recommended for fatigue cycling when long-term thermo-mechanical fatigue (TMF) data are required on coupon-sized tension or compression specimens. Long term durability testing plans for polymer matrix composite specimens are included in this report.

14. SUBJECT TERMS
Polymeric matrix composites (PMC); Thermo-mechanical fatigue; Long term durability; Candidate HSCT composites; High Speed Civil Transport (HSCT); Thermal-actuated compression and tension fixtures; Hydraulic-actuated fixtures; Thermal chambers

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