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DESIGN AND DEVELOPMENT OF A LINEAR THERMAL ACTUATOR

Gerry Bush and Don Osborne*

ABSTRACT

The design and development of a Linear Thermal Actuator (LTA) for space applications is described. The actuator is driven by thermal energy and utilizes the property of thermal expansion to do work. Equations to predict performance are developed and used to optimize the design of the Development Model LTA. Design details and test results are presented and discussed.

INTRODUCTION

Concept

An LTA is a device which, when subjected to a change in temperature by the addition or extraction of thermal energy, causes work to be done by the movement of an actuator rod against some external resisting force (Figure 1). The principle of operation through which the actuation is achieved is based on the expansion or contraction of a large number of plates, packaged in such a manner that variations in lengths ue to temperature changes are combined.

Applications

The LTA is inherently a high force/low displacement type mechanism, although larger displacements can be obtained by using the LTA with the appropriate linkages. Applications under consideration are:

1. Antenna Pointing Mechanism

   A number of spacecraft require active antenna positioning. Depending on required response time and positioning accuracy the LTA is a viable candidate.

2. Deployment Mechanism

   As a high force mechanism the LTA is well suited for use in deploying structures. It also has a retraction capability which is attractive in light of recent Space Shuttle missions which have demonstrated the capability to retrieve satellites.

3. Thermal Control System

   The LTA can generate sufficient force to make conductive couplings to radiator panels. As spacecraft temperature increases, the LTA actuator moves making conductive couplings to a radiator plate. The result is a simple thermal control system.

* Spar Aerospace Limited, Ste. Anne de Bellevue, Quebec, Canada

Objectives

The project goal was to design, manufacture and test a product for space applications based on the above concept. It was to be compact, highly reliable and have desirable performance characteristics. Performance objectives and test results for the Development Model LTA are given in Table 1. Where test results are not yet available, calculated values are presented.

TABLE 1: LTA PERFORMANCE SPECIFICATIONS

CHARACTERISTIC	OBJECTIVE	TEST RESULTS
Displacement Range	8.5 mm	12.0 mm
Maximum Applied Load	± 50 N	± 100N
Repeatability (% of peak to peak displ.)	± 2.5	± 1.0
Non Linearity (% of peak to peak displ.)	Minimize	
Due to Friction		± 2.5
Due to Backlash		± 9.0
Response Time (End to End)		
Heating	5 min	10 min**
Cooling	5 min	180 min**
Power Consumption		
Heating	-	150 W max
Cooling	-	0 W
Position Maintenance	10 W max	10 W max**

**Calculated values - test results not yet available.

Configurations

Three configurations were proposed at the start of the project. Two of the arrangements were based on planar components. In the symmetrically loaded planar arrangement, the actuator rod was located in the center of the plate assembly. In the unsymmetrically loaded planar arrangement, the actuator rod was located on one end of the plate assembly as shown in Figure 1. The third arrangement was based on cylindrical elements which assemble one inside the other.

A trade-off analysis was performed to determine which configuration was best. The trade-off study gave high weighting to reliability, a large displacement range against design external loads, repeatable temperature/position actuation with minimum nonlinearity, quick response, compactness, low weight, and minimal power consumption during position maintenance.

The unsymmetrically loaded planar arrangement was chosen because of its ability to be manufactured to analytic predictions for a weight optimal design with no significant penalty to other criteria.

Plate Joining Techniques

A major task in the development of the LTA was to determine a suitable method of joining the ends of the high and low expansion materials. A mechanical joint was selected to avoid high temperature fatigue and strength problems associated with adhesives and solders. Interlocking tabs were developed which are capable of two way operation, do not degrade at elevated temperatures, and can be manufactured to strict tolerances.

Plate Materials

Ideally, a plate material has a high modulus of elasticity, low density, very high or very low coefficient of thermal expansion and a high strength. A high thermal conductivity and low thermal capacitance is desirable for the high expansion plate.

Invar and Graphite Fiber Epoxy Composite (GFEC) were found to be most suitable for use as low expansion materials. Aluminum and Magnesium were found to be best for use as high expansion materials. Invar was selected over GFEC for the low expansion material as it has a much higher shear strength which is required by the interlocking tab joining technique. Aluminum was chosen over magnesium because it behaves more predictably and has a higher yield strength.

DESIGN AND PERFORMANCE EQUATIONS

Displacement

Actuator position was found to be dependent on the following four items, the first being the desired effect.

1. Change in plate length due to thermal expansion when subjected to a change in plate temperature.

2. Change in plate length due to plate clasticity when subjected to a load.

3. Opposition to changes in plate length as a result of the static coefficient of friction and normal forces.

4. Backlash because of clearance at the interlocking tabs and/or clearance between the plate assembly and the casing wall whenever the load is reversed.

The effect of the first two items above can be best illustrated by considering a single plate as shown in Figure 2. It has length l, cross sectional area A, applied load P, and is subject to a temperature change T. The total deflection is equal to:

$$\delta_1 = (\alpha T - \frac{P}{AE}) \quad (1)$$

E = modulus of elasticity
α = coefficient of thermal expansion

Extending this analysis, an equation can be developed to handle the more general case of an LTA with two materials and multiple plate pairs. It is assumed that the cross sectional areas of all plates of the same material are constant and that the total plate length of each material is equal to L. Properties of the high expansion material are designated with the subscript 1, those of the low expansion material with the subscript 2.

$$\delta = L\left(T(\alpha_1 - \alpha_2) - P\left(\frac{1}{A_1E_1} + \frac{1}{A_2E_2}\right)\right) \quad (2)$$

An equation was also developed to predict the effect of static friction on plate actuation which is a function of the static coefficient of friction, assembly preload due to plate warpage, and applied load. For the load range under consideration, its effect on displacement is less than $\pm 2.5\%$.

Weight and Volume Minimization

An analysis was performed to determine the values of the design parameters which minimized weight and volume for a given load and displacement. This was accomplished by specifying the weight of the LTA plate assembly as follows; where ρ represents the material density:

$$W_t = A_1 L \rho_1 + A_2 L \rho_2 \tag{3}$$

Equation (2) can be rearranged to solve for L and substituted into Equation (3). The resulting equation has only two variables A_1 and A_2. Taking derivatives and setting them equal to zero yields equations for the cross sectional areas which minimize weight.

Calculations were also performed to find the plate width and number of plates which minimize LTA volume. The smallest volume occurs when the plate assembly, including space for actuation, takes the shape of a cube. While this shape is not normally ideal, it does provide a useful baseline to which more desireable shapes can be compared.

Response Time

One of the design objectives for the Development Model LTA was to limit power consumptions during position maintenance to a maximum of 10W. To accomplish this it was necessary to isolate the LTA from the environment using multilayer thermal blankets and nonconductive mounting shims. Because the losses are so limited, the LTA can be treated as an isothermal block for the purposes of analysis.

During heating the response time is limited by available spacecraft power or heater capacity and the unit thermal capacitance. During cooling the response time is limited by the ability of the radiator plate to dump power to space and the unit thermal capacitance. The thermal capacitance of the Development Model LTA is calculated to be 491 J/^{o}C.

DESIGN AND MANUFACTURING

The Development Model LTA consists of a number of components and assemblies. A sample of each of the components is shown in Figure 3.

Casing

The casing, shown in Figure 3 and Figure 4, is used to hold the plates in position and constrain the motion of the actuator rod. The interior of the casing is coated with dry film lubricant to reduce friction and wear between the plates and the casing. One side of the casing is coated with white paint to act as a radiator plate and dissipate heat to space. Thermistors are mounted on the ends of the casing to monitor temperature. The casing is shown resting on thermal shims which are made of polyimide.

The LTA was covered by the multilayer thermal blanket shown in Figure 3. The large rectangular cutout allows the white painted radiator surface to view space.

Plate Assembly

The plate assembly is made up of 33 aluminum plates and 32 Invar plates. A set of aluminum plates consist of 1 actuator end plate, 10 heater plate assemblies, 18 high expansion plates, 3 thermistor plates and a fixed end plate assembly. One of each of these is shown in Figure 3. The plate in the foreground is a thermistor plate. The remaining aluminum plates are shown in the order mentioned, separated by Invar plates, from left to right. All plates are coated with dry film lubricant.

Details of a high expansion plate and a low expansion plate are shown in Figure 5. The Invar plate has a thickness of .64 mm. The aluminum plate is .94 mm thick and has a pocket .47 mm deep. Both plates have weight optimal cross sectional areas. The slot and the hole in the aluminum plate are used to pass wires for heaters and thermistors through the plate assembly. The tabs on the aluminum plates are 12.5 mm long as compated to 2.5 mm long for the Invar plates. The tabs were lengthened to reduce bending stresses and plate assembly elasticity as a result of any clearance between tabs. It is planned to increase the length of the tabs on the Invar plates for all future LTAs.

Figure 6 shows details of the fixed end plate. The right end of the plate has a single tab on the back which fits into a slot in the casing. A thermistor is mounted in the pocket to monitor plate temperature. The tabs at the left end are similar for all aluminum plates. Figure 7 shows details of the heater plate assembly. It has tabs on both ends and a Kapton film heater bonded into the pocket.

TEST RESULTS

Figures 8 through 15 show test results for the Development Model LTA. The first six curves show actuator displacement as a function of temperature under different loading conditions. The remaining curves give the transient heating and cooling response for two different power inputs. In general, results match theoretical predictions well. Variations occur as a result of backlash and increased elasticity of the plate assembly. Theoretical curves neglect the effect of backlash and friction.

The backlash is apparent only under no load conditions and is of the order of 2.1 mm. It can be viewed in Figure 8. Friction effects can be considered negligible since the normal force is small under these conditions.

Figure 8 also demonstrates the high repeatability of the LTA by actuating through two complete cycles. For both the heating and cooling curve, the actuation follows the same path within $\pm 1\%$.

Figures 9 through 12 demonstrate performance under both compressive and tensile loading. In all cases the effect of plate elasticity is larger than that predicted by theory. This is apparent by the offset between theoretical and experimental results. The nonlinear effect of friction forces is also visible and can be seen to increase with increasing load as expected.

The heating portion of each of the displacement versus temperature curves is shown on one graph in Figure 13. The slope is the same for all curves. The effect of plate elasticity can also be seen by the separation between curves.

Figures 14 and 15 are heating and cooling curves for the Development Model LTA at room temperature and pressure. Under thermal vacuum conditions the heating portion of the curve will be sharper, as losses are limited to a maximum of 10 W. A longer cooling response time is also anticipated.

DEVELOPMENT PROBLEMS AND SOLUTIONS

A number of problems became apparent during testing at different stages. The most obvious are the nonlinearities as a result of backlash and friction.

Backlash was caused primarily by clearance at the tab joints and is seen as a manufacturing problem. It was first noted during breadboard testing where more than .04 mm clearance per joint was evident. With 65 joints in the Development Model LTA even a small clearance is excessive. The proposed solution was to dimension the plates to obtain a light interference fit. This fit was clearly not achieved during manufacturing with the techniques used, however, the solution is still seen as viable.

The static coefficient of friction between the plates coated with dry film lubricant was found to be in the order of 0.35. When first assembled this high coefficient of friction, when combined with preload caused by plate warpage, causes significant binding of the actuator. The problem was reduced by increasing the clearance between the casing and the plate assembly to reduce preload. Decreasing preload by this method resulted in increased backlash and increased plate assembly elasticity.

As noted above, there was more plate elasticity than that predicted by theory. Clearance between the plate assembly and the casing wall allowed the tabs to rotate which induced the plates to assume buckling shapes in the space available. These actions led to increased elasticity. The tabs on the aluminum plates were therefore increased in length to reduce the amount of rotation possible for a given clearance. the ideal solution to this problem is to reduce the static coefficient of friction, which would allow tighter packaging of the plates.

CONCLUSIONS

The Development Model LTA has demonstrated the performance characteristics required for the target applications. It has responded in a predictable, repeatable fashion which has been successfully characterized. Both load and displacement obtained by the Development Model LTA have exceeded initial goals.

Future work will be directed towards developing a deployment/retraction mechanism for a flight project.

ACKNOWLEDGEMENT

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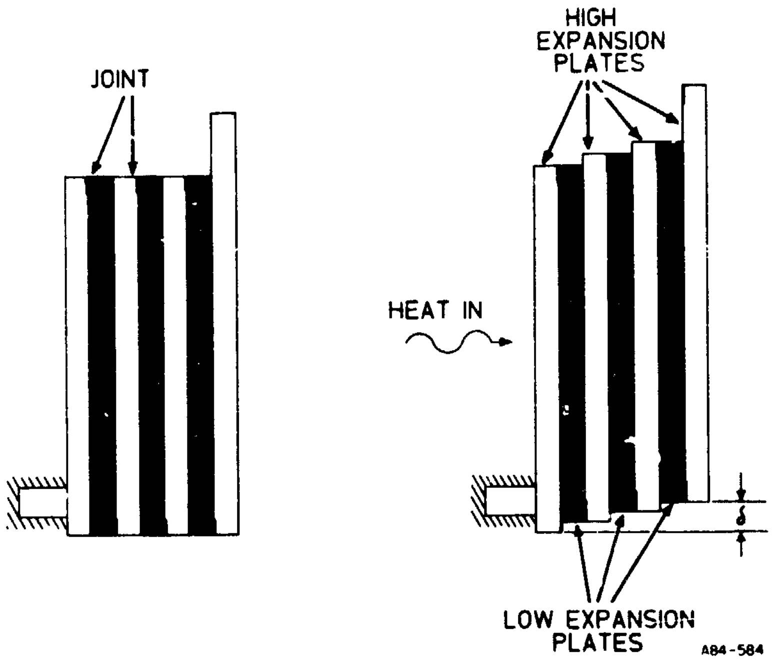

Figure 1. LTA Concept

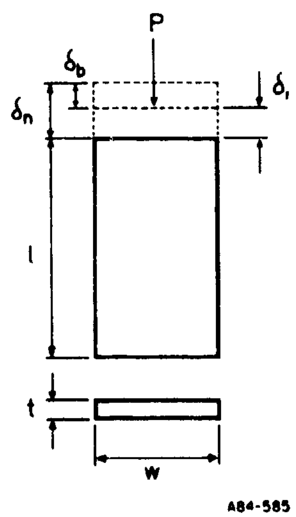

Figure 2. Displacement of a Single Plate

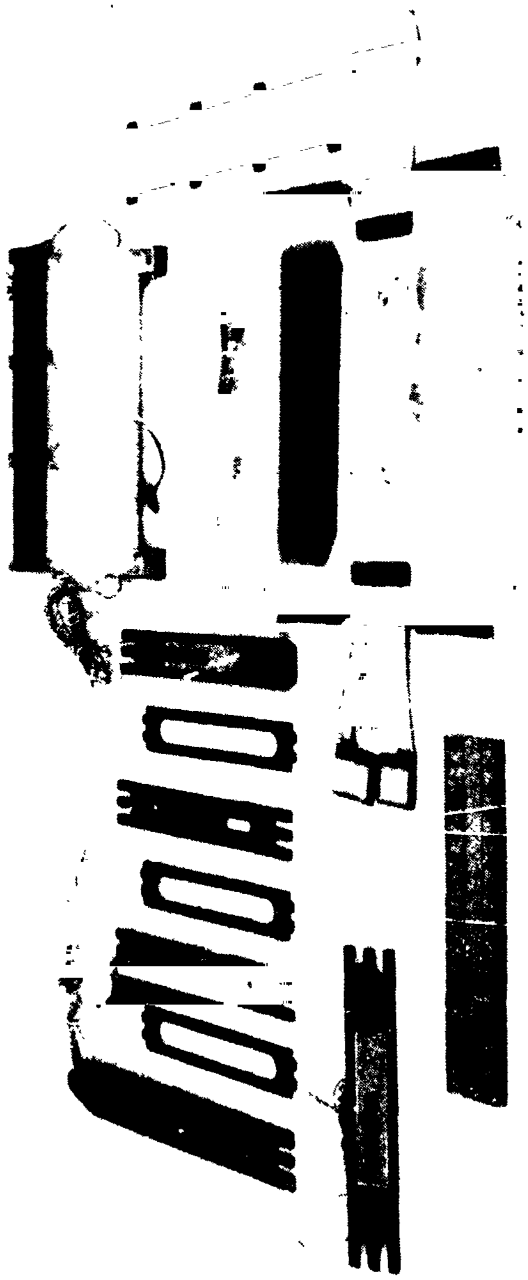

Figure 3. LTA Piece Parts and Low Level Assemblies

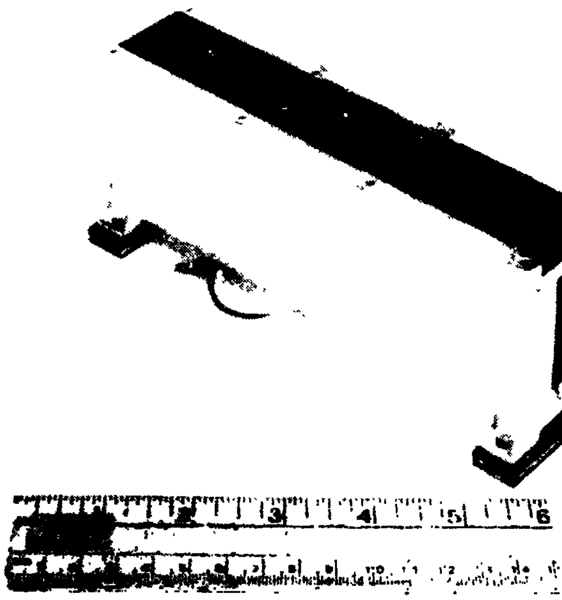

Figure 4. Casing A embly

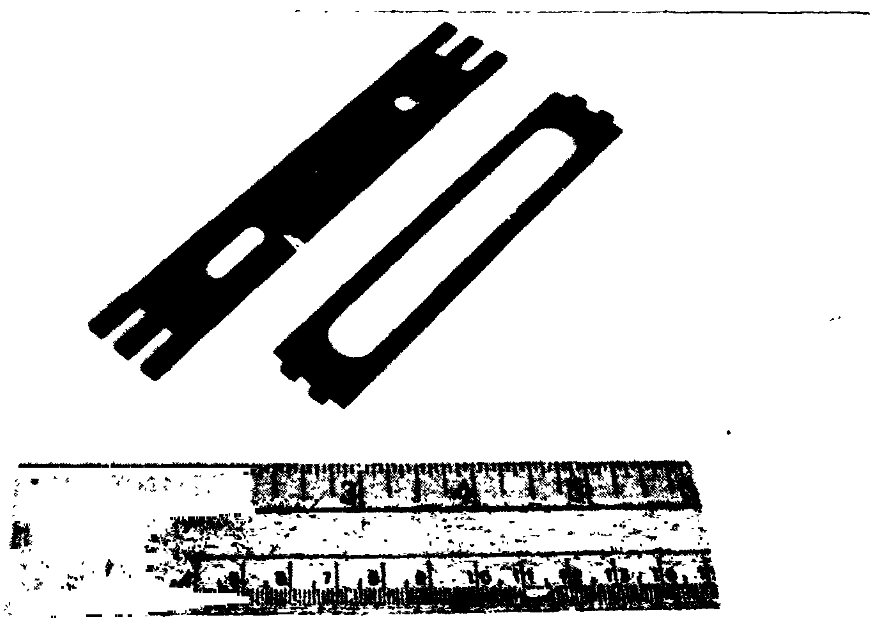

Figure 5. Sample High & Low Expansion Plate

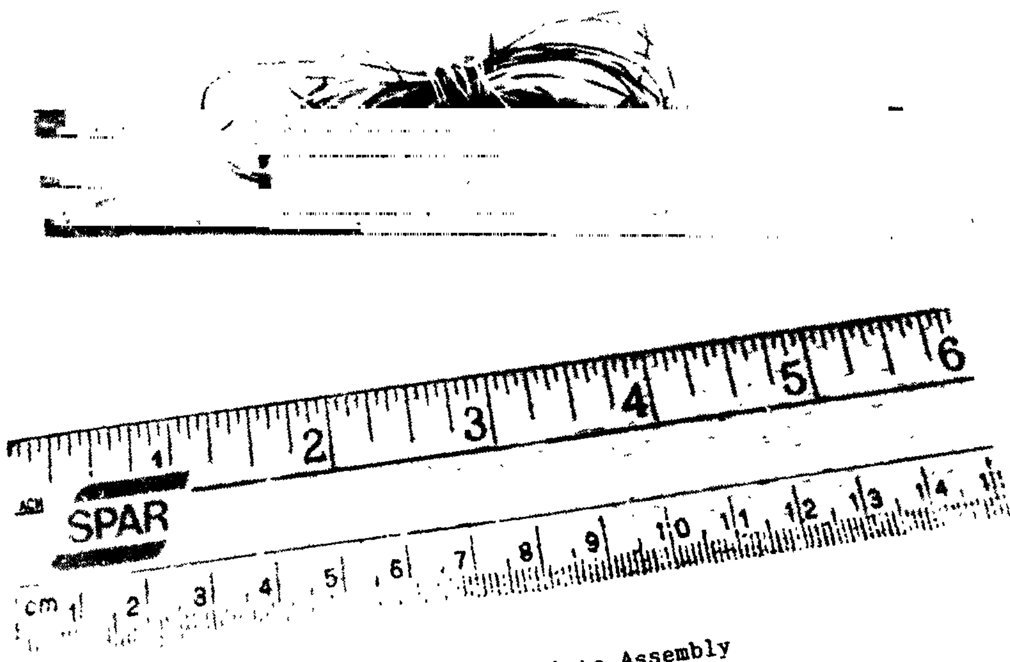

Figure 6. Fixed End Plate Assembly

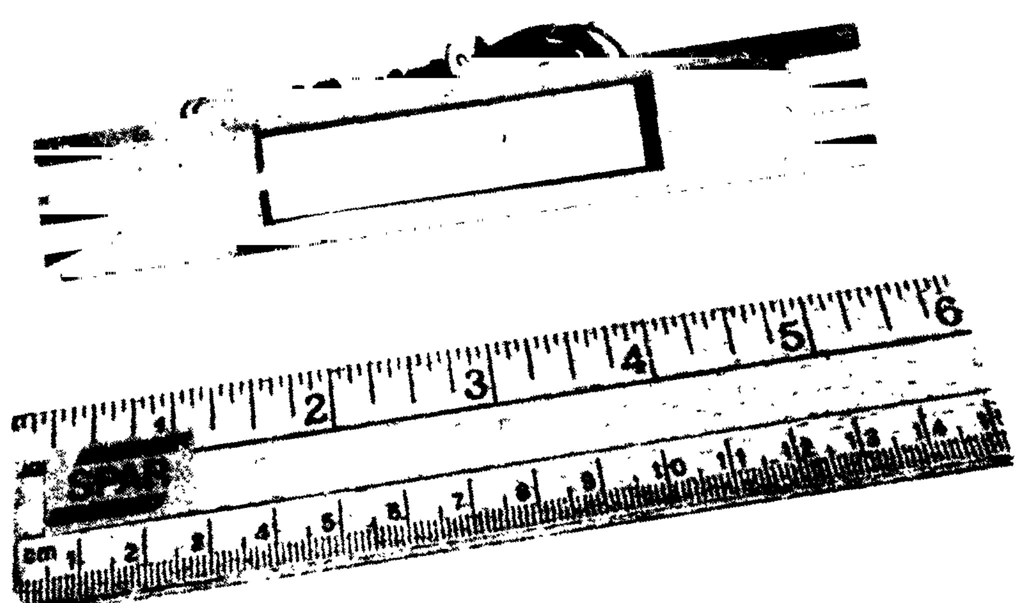

Figure 7. Heater Plate Assembly

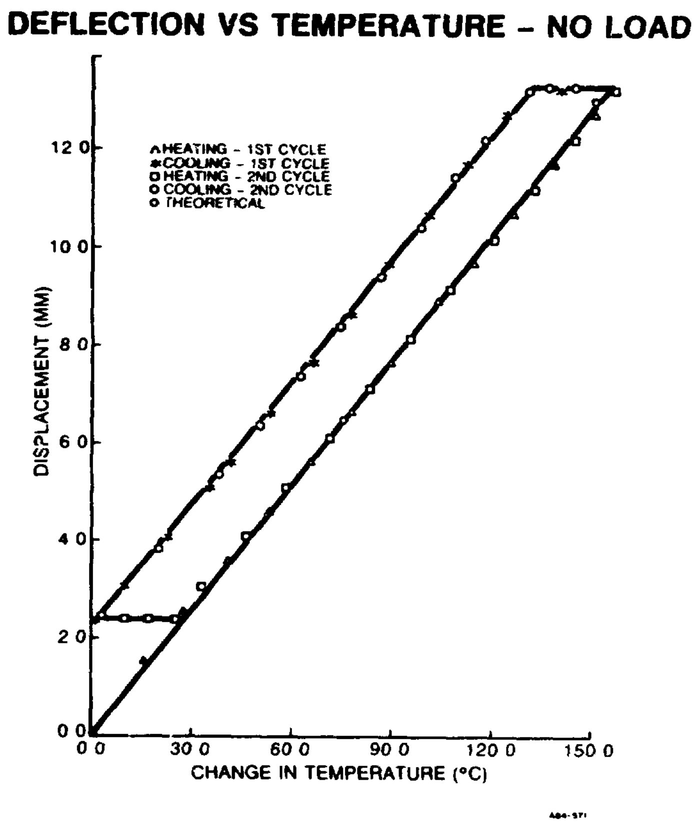

Figure 8. Displacement vs. Temperature No-Load

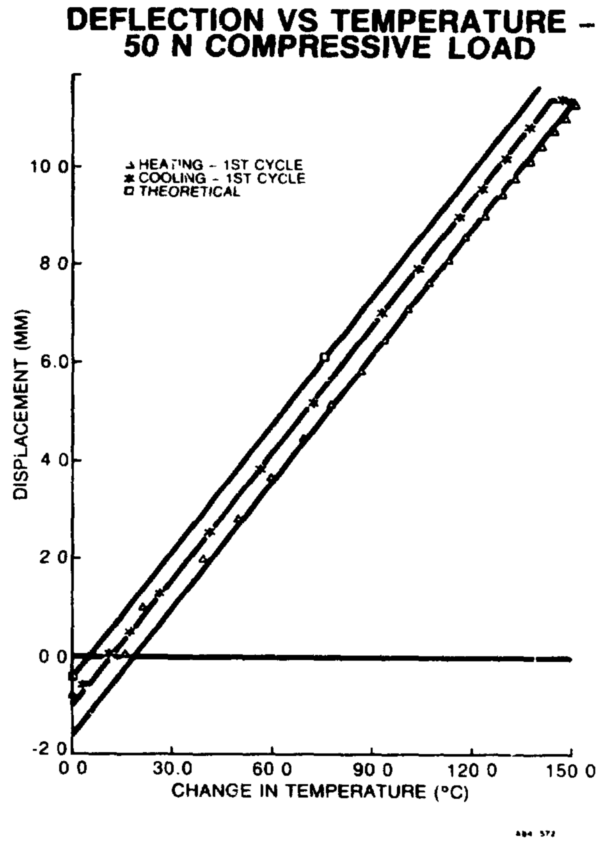

Figure 9. Displacement vs. Temperature 50 N Compression

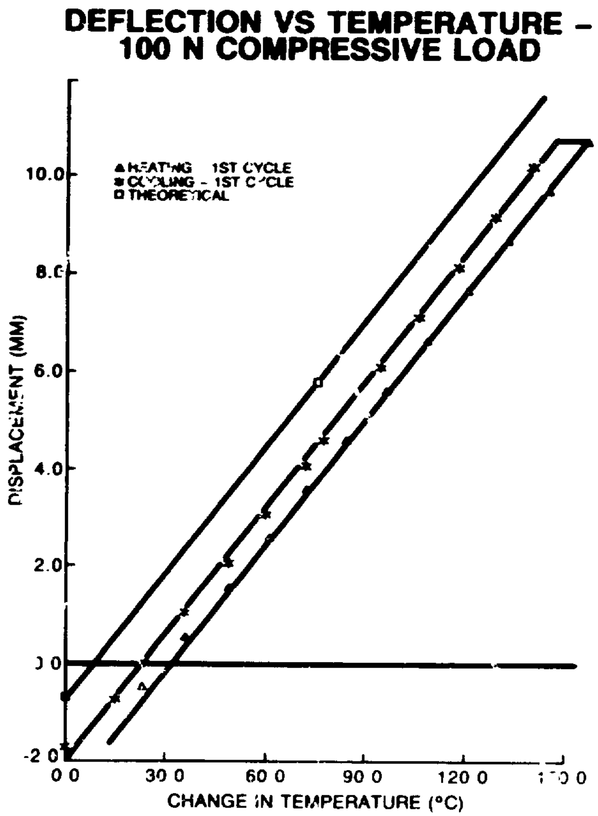

Figure 10. Displacement vs. Temperature
100 N compression

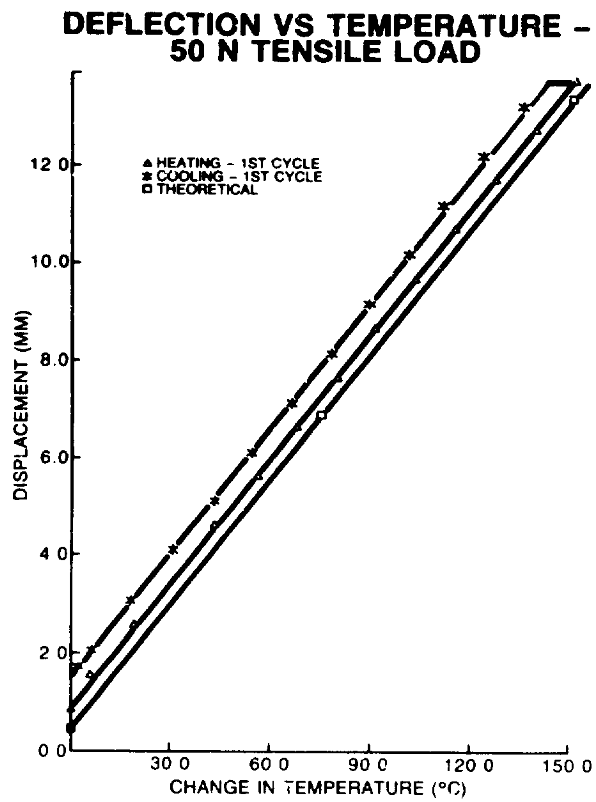

Figure 11. Displacement vs. Temperature
50 N tension

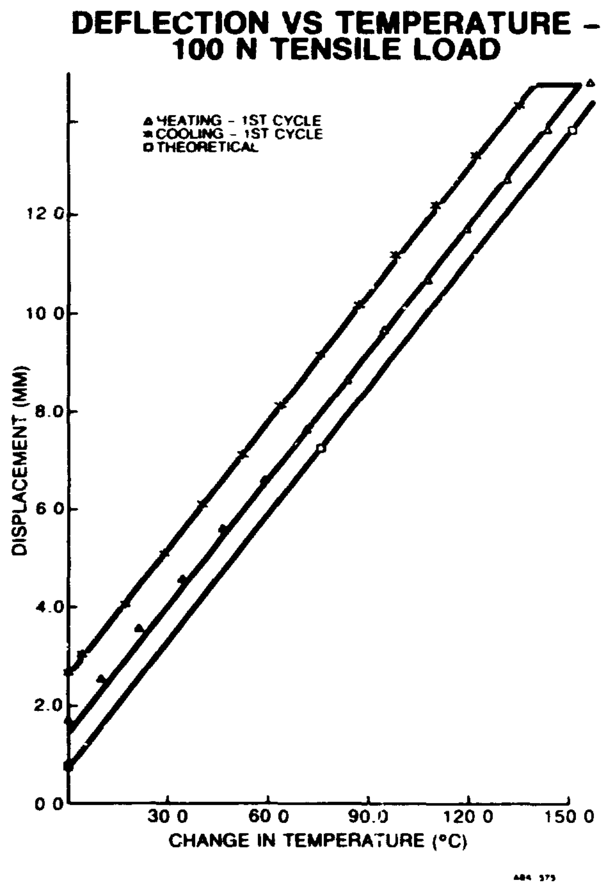

Figure 12. Displacement vs. Temperature
100 N tension

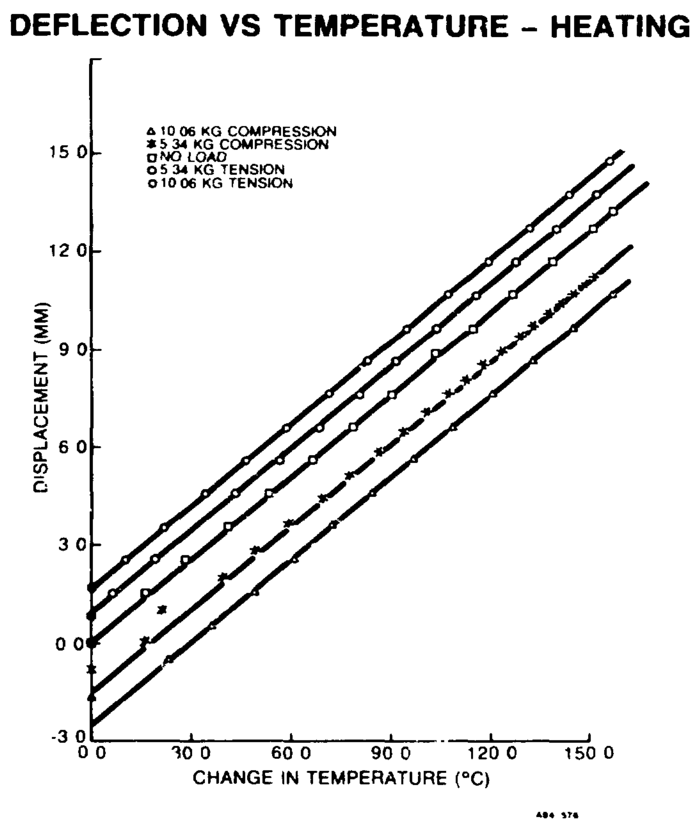

Figure 13. Displacement vs. Temperature
(Heating Curve Only)

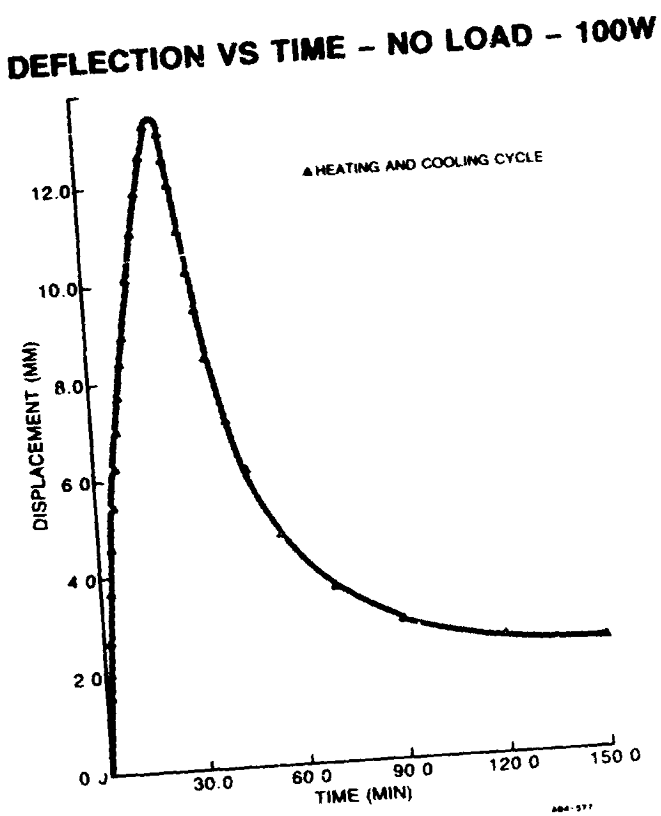

Figure 14. Transient Response
100 W Heating

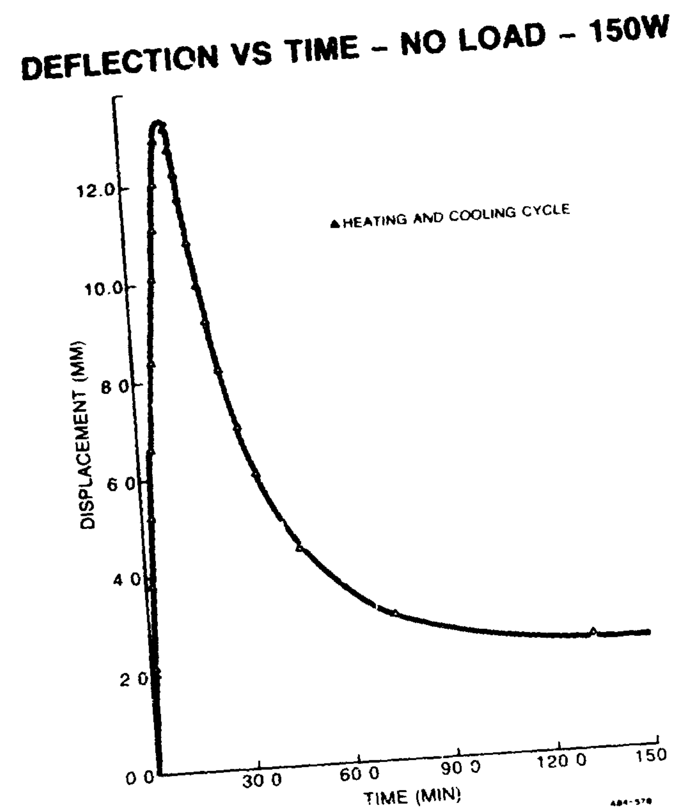

Figure 15. Transient Response
150 W Heating