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Delayed elasticity in Zerodur at room temperature

John W. Pepi, Donald Golini

Itek Optical Systems
A Division of Litton Systems, Inc.
10 Maguire Road
Lexington, Massachusetts 02173-3199

ABSTRACT

Much has been written about structural relaxation, viscous flow, delayed elasticity, hysteresis and other dimensional stability phenomena of glass and ceramics at elevated temperatures [1,2]. Less has been documented about similar effects at room temperature. The time dependent phenomenon of delayed elasticity exhibited by Zerodur has been studied at room temperature and is presented here. Using a high-performance mechanical profilometer, a delayed strain on the order of one percent is realized over a period of a few weeks, under low stress levels. An independent test using optical interferometry validates the results. A comparison to Corning ULE silica glass is also made.

The effect is believed to be related to the alkali oxide content of the glass ceramic and rearrangement of the ion groups within the structure during stress. The effect, apparent under externally applied load, is elastic and repeatable, that is, no hysteresis of permanent set, as measured at elevated temperature, is evidenced within measurement capabilities. Nonetheless, it must be accounted for in determining the magnitude of distortion under load (delayed elastic creep) and upon load removal (delayed elastic recovery). This is particularly important for large lightweight optics which might undergo large strain during fabrication and environmental loading, such as experienced in gravity release or in dynamic control of active optics.

1. INTRODUCTION

The delayed elastic effect presented in this paper was first observed during manufacture of the primary mirror segments for the Keck Telescope program. It is important to note that these effects in no way affect the performance of the telescope, currently one of the largest under construction in the world today, since the delayed strain is fully accommodated in analysis, test, and final assembly.

The 10-m-diameter Keck Telescope consists of 36 1.8-m-diameter, off-axis, hyperbolic, hexagonal mirror segments. These are composed of near-zero-coefficient-of-expansion glass ceramic Zerodur substrates, manufactured by Schott Glaswerke of Mainz, Germany. The blanks are approximately 1.9 m in diameter and 7.5 cm thick. To produce the aspheric segments (consisting of six different configurations) in a timely fashion, scientists at the University of California have developed the technique of stressed mirror polishing [3,4]. This method employs the introduction of shears and moments about the segment periphery, in its circular shape, to bend the mirror into the reverse of the desired shape. A true sphere is then ground and subsequently polished into the segment, after which the loads are removed and the desired optical prescription obtained.

The process involves theoretical prediction of the loads required to bend the surface, and iterative solutions based on test measurements to fine-tune the desired shape. The aspheric shape required for the Keck Telescope segments is such that it can be described by a series of Zernike polynomials through fourth order, achieved by a series of variable loadings of both shear and moment applied to the circular segment periphery. These must be reacted by a continuous elastic support distributed over the entire back surface. In actual practice, the various edge load conditions are achieved through a series of levers and linkages to which weights are applied through simple buckets, as shown in Figure 1. The continuous back support is provided by a series of fluid pistons at 67 discrete locations provided by the combination fabrication and metrology mount shown in Figure 2.

2. OBSERVATIONS

During stressing and unstressing of the Zerodur optical segments, measurements of the surface profile always indicated higher values than the theory, as validated by a detailed finite-element mathematic model, would suggest. Furthermore, measurements made over the period of time showed a continual increase in value. Finally, measurements after release of stress following several weeks of stressing were always higher than measurements made while going to the stressed condition initially.

As might be expected, several possible sources explaining these observations were possible, since the amount of measurement change with time was on the order of a few tenths of a micron. To measure such effects without the use of interferometry was certainly suspect. Additionally, the fluid mount supporting the optic was subject to concerns of stabilization after load application and removal. Finally, clamping loads and thermal changes could cause errors in the optic as a function of time. All these sources could give the appearance of creep in the glass and are briefly discussed in the paragraphs below.

3. MEASUREMENT

A typical plot of the surface profile after stressing is shown in Figure 3 as a function of time. This curve is generated after removal of the loads for one of the innermost diameter segments whose deflection magnitude is shown in Table 1. As evidenced in the table, the predominant change is in the power (focus) term. The curve is generated by measuring along a diameter of the optic using a multi-point profilometer placed on the surface. The profilometer consists of a graphite-epoxy beam in which are housed electronic linear variable displacement transducer (LVDT) probes as shown in Figure 4. Tied to a personal computer, measurements are set to be read every 5 minutes for 4 hours in the presented case. When shown as a function of probe location in Figure 5, it can be seen that a power term drift with time is realized.

4. ERROR SOURCE

As noted earlier, measurements to the one-tenth-micron level are subject to error in the metrology source and support system. As shown in Figure 6, the graphite-epoxy beam itself was subject to changes in the laboratory environment, which was controlled to ±10% Rh and ±1°C respectively. Short-term changes were also realized in the beam, due to creep instabilities under loading and thermal gradients that might exist due to the small heat source of the probes. As little as a 0.1°C gradient could cause the time drifts being witnessed. To alleviate this concern, it was noted that the beam instabilities were random, while measurements made such as those shown in Figure 3 after unstressing were not. Measurements made in unstressing a piece that relaxed a segment to a concave shape continued to drift concave; those made stressing a segment to a convex shape continued to drift convex.

The probes themselves were subject to drift due to a small change in electric current dependent upon the position of the LVDT probe in its range. These drifts, however, were random. Furthermore, the time constant of drift was on the order of minutes and not the hours being realized. To improve measurement accuracy, the drift problem was solved by adding resistance circuitry and a logic switch to the software, which accounted for the probe position in range. As the program evolved, a new and dimensionally stable graphite-epoxy beam, manufactured by Composite Optics, Inc., of San Diego, replaced the original beam and exhibited none of the instabilities noted earlier. The probes, too, were replaced with modified hardware supplied by Schaevitz Engineering. The measurement tool was determined to be accurate to 0.1 μm peak, or 25 nm rms, for distortions through fourth order. Nonetheless, the witnessed drift after stressing and unstressing remained.

The fabrication/metrology mount, which used water to float the optic during fabrication and test, was tested to determine settling constants after loading and unloading. Again, time constants are on the order of minutes, and were not enough to explain the much longer delays being witnessed.

Lastly, temperature changes in the room were monitored to determine any effects of hardware attachment to the glass. Results of analyses showed that temperature changes would have to be both systematic and significantly higher than were being measured to be of any concern.

5. DELAYED ELASTICITY

The observations recorded could be explained by creep of the ceramic at room temperature under load and delayed recovery upon removal. A review of the literature revealed that, based on experiments done during the earlier part of this century, such effects are possible. Various arguments have been set forth, to explain both the cause and the reality of the observed effects of room temperature, as well as their relationship to total loading time, and methods of load application. Interesting treatises on the subject have been made by several investigators and these references are noted herein. Most of the later work on delayed elasticity[5,6,7] has been centered at temperatures considerably higher than room temperature, where the delayed strain is significantly higher and more easily measured. At such elevated temperatures, viscous flow occurs, and several references[8] attempt to separate viscous flow (permanent hysteresis) from the delayed elastic effect, which is fully recoverable. Scherer[9] presents an excellent treatise on the theoretical aspects of both delayed and viscous effects. This paper does not attempt to discuss the theory, leaving such a discussion to the more esoterically inclined. A general consensus, however, is that the delayed elastic effect is more pronounced as the alkali oxide content of a glass or ceramic increases, due to rearrangement of the ion groups within the structure during stress.

Perhaps the results of the subject experiment using Zerodur can best be compared to work done by Murgatroyd[10] on vitreous silica and sheet glass. In those room temperature experiments, a small delayed elastic effect was observed that increased with the addition of oxides other than SiO_2. For vitreous silica (99.86% SiO_2), the observed delay was 0.1% of the total strain. Murgatroyd's measurements were best represented by a simple relationship in which the strain was proportional to the logarithm of time. The results of the Zerodur experiments for two of the Keck program's innermost segments are shown in Figure 7 as a function of log time and follow the Murgatroyd curves quite well. Murgatroyd found the effects to be reversible and dependent upon the time of loading but not on the stress level; that is, the percentage of delayed to total strain is a constant. For the Zerodur ceramic materials reported upon here, stress levels in the optic are on the order of 100 psi only. When extrapolated to several weeks of loading, a delayed elastic strain of nearly 1% (10 times that of vitreous silica) is realized.

6. VALIDATION

To further confirm the Keck data for delayed elasticity, additional experiments were conducted on both Zerodur and ULE. The samples used were two 5-inch-diameter stress relieved plates polished flat on one side. The Zerodur was a piece taken from an actual Keck blank. Measurements were made using interferometry to eliminate metrology errors and to verify the performance of the mechanical profilometer.

A thin Zerodur plate was polished optically flat on one side and acid etched for stress relief on the sides and edges. The plate is 5 inches in diameter and 0.2 inches thick. A 30-kilogram load was applied over the central inch of the plate while it was supported at three edge points, 120 degrees apart. Before applying any load, a baseline measurement of the plate was taken interferometrically while supported at three edge points. The load was then applied for 2 weeks at room temperature. Upon unloading, the blank was measured interferometrically over time. Sixteen interferograms were taken 5 minutes after unloading, and this was repeated after the following increments: 10 minutes, 50 minutes, 3 hours, 24 hours, 5 days and 12 days. At each time interval, sixteen interferograms were averaged. Each average was subtracted from the baseline condition of the plate and Zernike polynomials were fitted to the subtractions.

Based on the Keck experience at Itek, we predicted the delayed elastic effect to be about 0.7% strain residual on the Zerodur blanks immediately after unloading. The setup was modeled with NASTRAN and the predicted deflections were characterized as Zernike polynomials. The instantaneous delayed elasticity expected was 0.7% of the maximum deflection, while the approximate theory, based on the Murgatroyd studies, would indicate the figure of the plate to return to its original condition linearly with log time over a period equal to the loading time (the actual theory shows the delayed strain to behave as an exponential function of time, for which the logarithmic expression is reasonably valid away from the zero and infinite time extremes). The actual data is plotted as focus (Z5, C(2,0)), tricorn (Z10, C(3,3)), and third-order spherical aberration (Z13, C(4,0)).

Figure 8 may be compared to the predictions. The correlation is excellent. These are the only significant Zernikes that are affected in the NASTRAN model, and they are also the only Zernikes that were significant in the measurement. The average rms noise in the sixteen picture interferograms is 0.01 microns rms (approximately 0.05 microns p-p).

The experiment was carried one step further. According to the theory, the delayed elastic effect should be minimal in materials with a negligible alkali oxide content. To test this theory, we repeated the above experiment using ULE instead of Zerodur. The data shown in Figure 9 shows that five minutes after unloading, there is no measurable delayed elastic effect in ULE, for any of the polynomial terms, as predicted.

This experiment was highly significant for several reasons. For one, the phenomenon observed during the Keck stress mirror polishing process was not a metrology problem but rather a delayed elastic effect. This experiment used a simple kinematic support for the test flat and Fizeau interferometry (averaging sixteen interferograms for each data point) for metrology, and the delayed elastic effect agreed extremely well with the Keck data. The experiment also showed that there is no delayed elastic effect in ULE, within measurement capability, beyond that of vitreous silica, which we attribute to the lack of alkali oxides.

CONCLUSION

Based on several tests, a delayed elastic strain of up to 1 percent is found for Zerodur at room temperature after several weeks of loading. The effect is nearly an order of magnitude higher than that of vitreous silica or ULE.

Within measurement capability, it is fully reversible; i.e., elastic and without hysteresis. It should, nonetheless, be accounted for when measuring to the stringent optical tolerances of a fraction of wavelength of light. This is particularly important for optics that might undergo large strains during fabrication or environmental loading, such as in gravity release or dynamic control of active optics.

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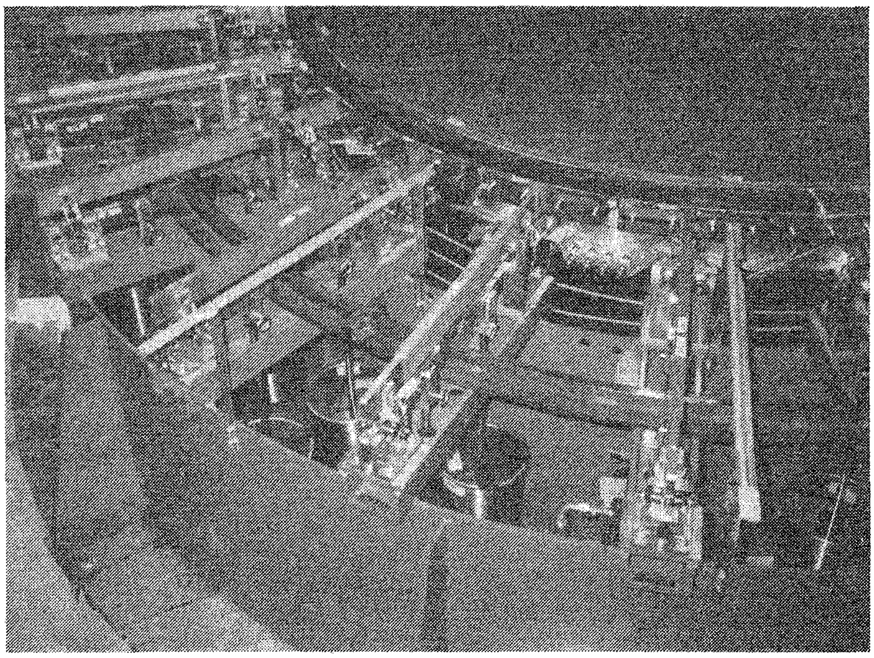


Fig. 1. Stressing fixture.

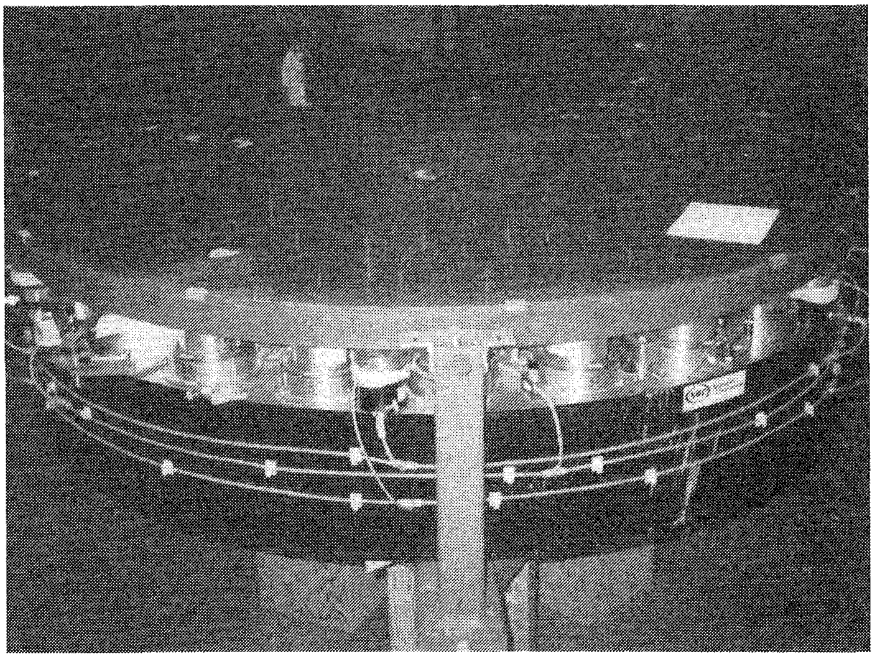


Fig. 2. Fabrication/metrology mount.

Fig. 3. Mirror distortion after unloading segment.

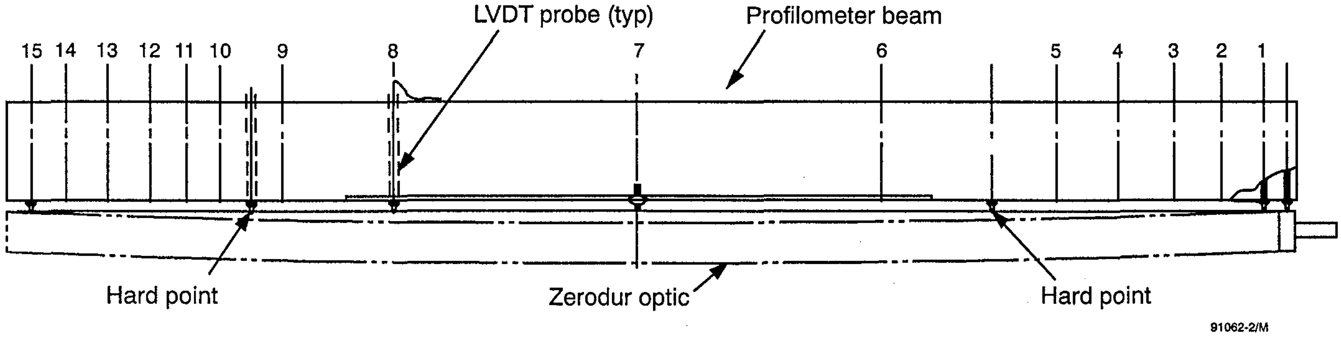


Fig. 4. Multi-point profilometer.

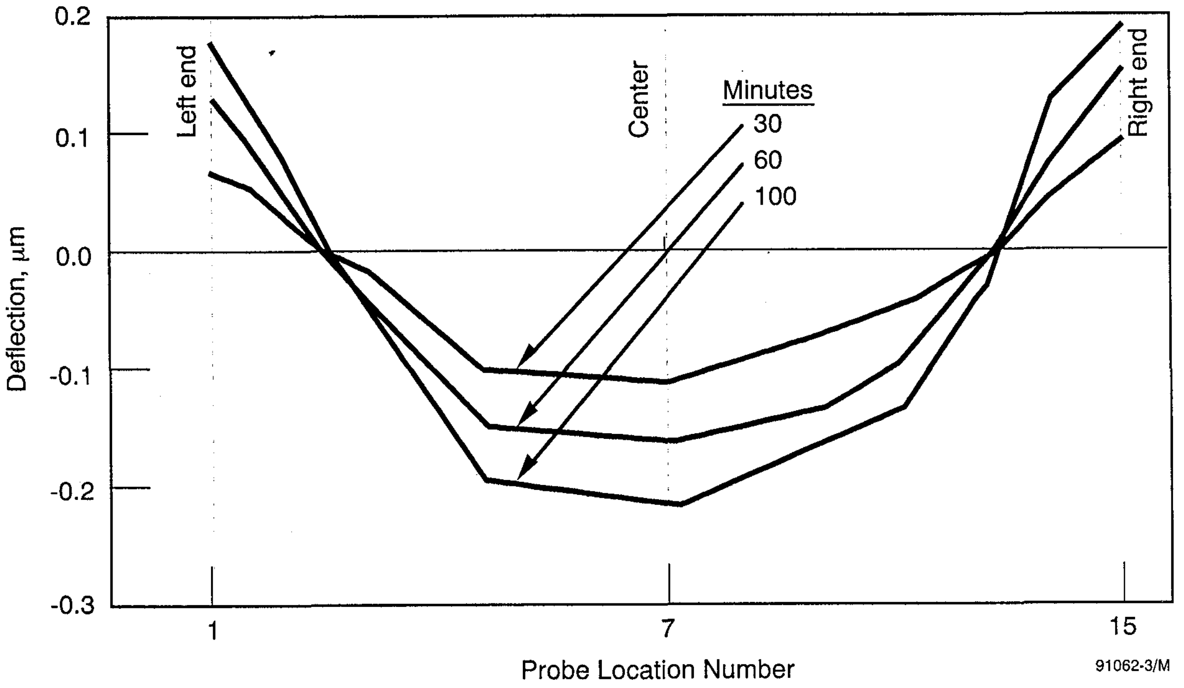


Fig. 5. Time constant evaluation.

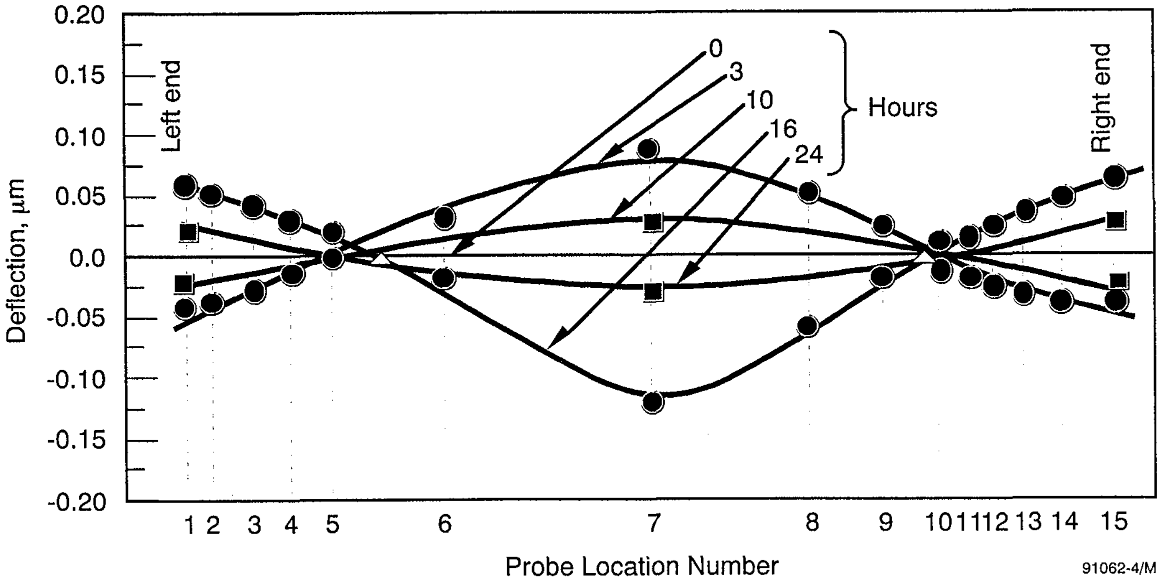


Fig. 6. Long-term profilometer stability.

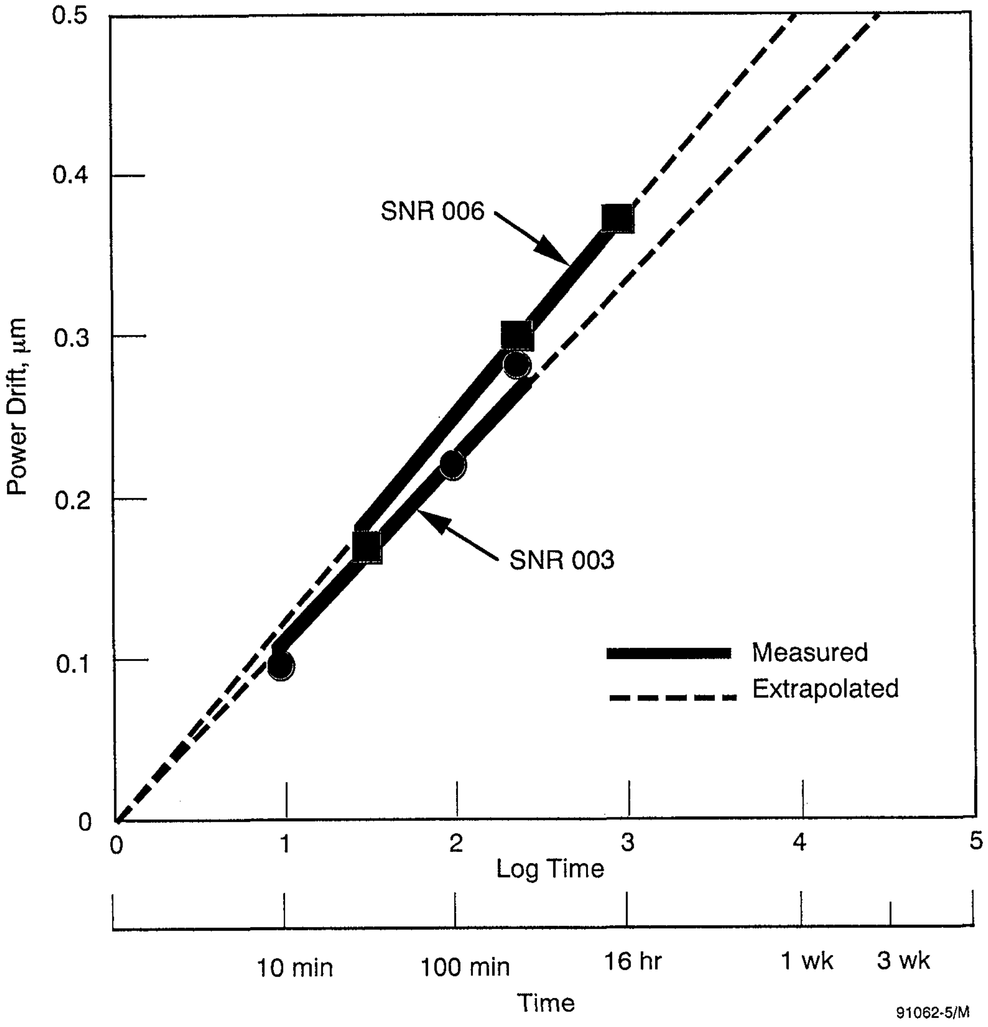
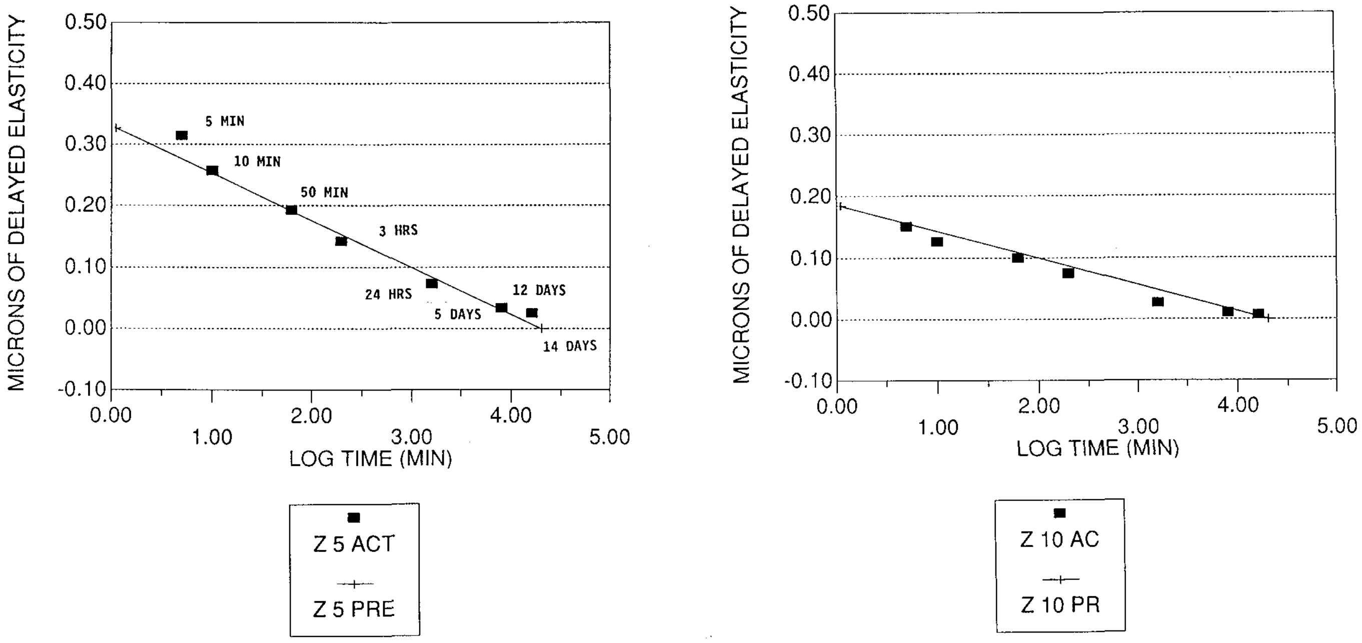
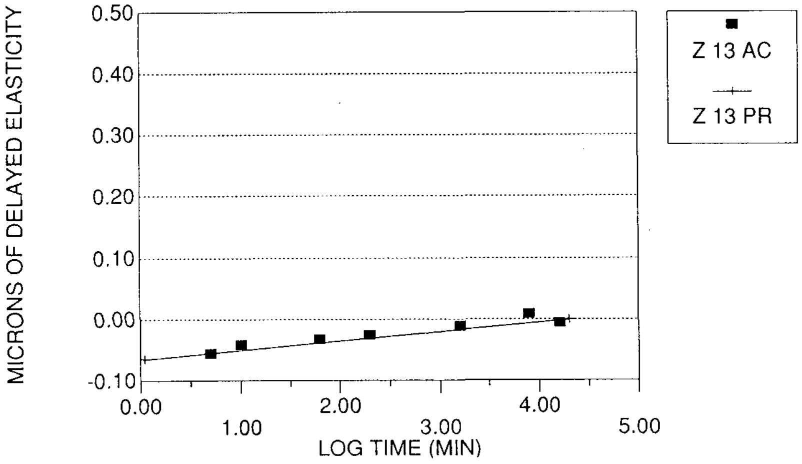


Fig. 7. Delayed elastic effect in Zerodur (stress approximately 100 psi).



(a) Delayed elasticity after 2 weeks loading (30 kg) in Zerodur.

(b) Delayed elasticity after 2 weeks loading (30 kg) in Zerodur.



(c) Delayed elasticity after 2 weeks loading (30 kg) in Zerodur.

Fig. 8. Delayed elasticity over time — actuals (squares) vs. predicted (line) in Zerodur for Z(5), Z(10), and Z(13).

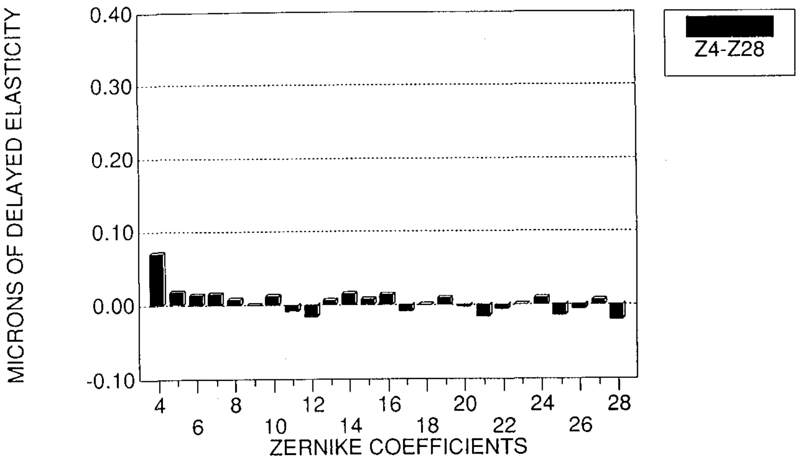


Fig. 9. Delayed elasticity in ULE after 2 weeks loading (30 kg) measured 5 minutes after unloading.

Table 1 — Desired Stressed State, Inner Segment Type

Index No. Zernike Coefficient		Distortion Peak, μm
4	C(2,-2)	0
5	C(2,0)	-78.0166
6	C(2,2)	12.81
7	C(3,-3)	0
8	C(3,-1)	0
9	C(3,1)	5.194
10	C(3,3)	-0.008
11	C(4,04)	0
12	C(4,-2)	0
13	C(4,0)	-0.0525
14	C(4,2)	-0.002
15	C(4,4)	0