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Unstable Optics

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1. INTRODUCTION

Especially for space applications, the problems of seeing are being superceded by the problems of dimensional changes in remotely located optical systems. Conditions of operation, in addition to launch considerations of acceleration and weight, often include

- vacuum environment
- thermal cycling over wide temperature ranges
- irradiation
- passage of considerable time without replacement
- fixed focus.

In choosing materials, the usual figures of merit, shown in Table I, are a good starting point, but ignoring other considerations can lead to disaster. We discuss below a number of these considerations.

Table I. Figures of merit for optics systems materials.

1. Structural
   a. Specific stiffness
   b. Fundamental frequency
   c. Dynamic response
   d. Shear modulus
   e. Fracture toughness
2. Temporal stability
   a. Microyield stress
   b. Dimensional instability
3. Thermal stability
   a. Thermal distortion parameter
   b. Thermal diffusivity
   c. Homogeneity of thermal expansion
   d. Thermal expansion match

2. THERMAL EXPANSION VERSUS TEMPERATURE

Most people realize that the thermal expansion coefficient,

$$\alpha \equiv \frac{1}{L}\frac{\Delta L}{\Delta T},$$

varies with temperature, going to zero for all materials at T = 0 K. This property is shown in Fig. 1 for some common materials. As we develop more applications for space, we must pay more attention to the big picture with regard to temperature (from absolute zero upwards). In addition, manufacturers should desist from using a single value to describe the expansivity of their material over a temperature range. A single value may not reflect that the material's expansivity crosses zero somewhere in that range. It might be better to describe the boundedness of ΔL/L over that range, or to present pictorially both α(T) and ΔL/L versus temperature.

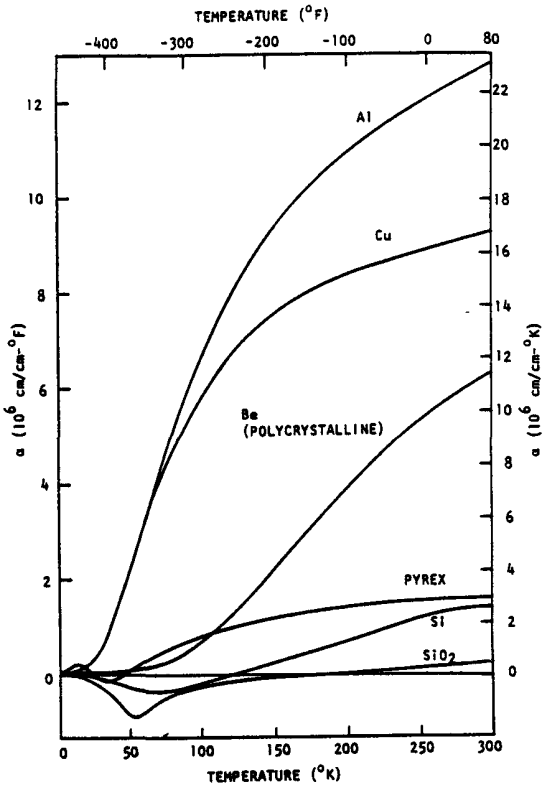

Figure 1. Thermal expansion coefficient versus temperature for some common materials.

We show in Fig. 2 the thermal expansivities of some of the lowest-expansivity materials currently available. The broad-ranging low expansivity of Corning 9600 is noteworthy, and we shall explore in later sections any drawbacks of this material. One could still wish for a material with such a broad-ranging, low expansivity, combined with great strength, like that of Invar. Composites such as graphite/epoxy attempt to satisfy that need.

For low-temperature applications, we should not overlook fused silica, for which zero expansivity occurs near 170 K. The excellent homogeneity of fused silica is described in a later section. As is well known, sometimes low expansivity is not as useful as is the close *expansivity match* between the optics and their mounting material. Figure 2 shows the close match between Invar and fused silica at room temperature.

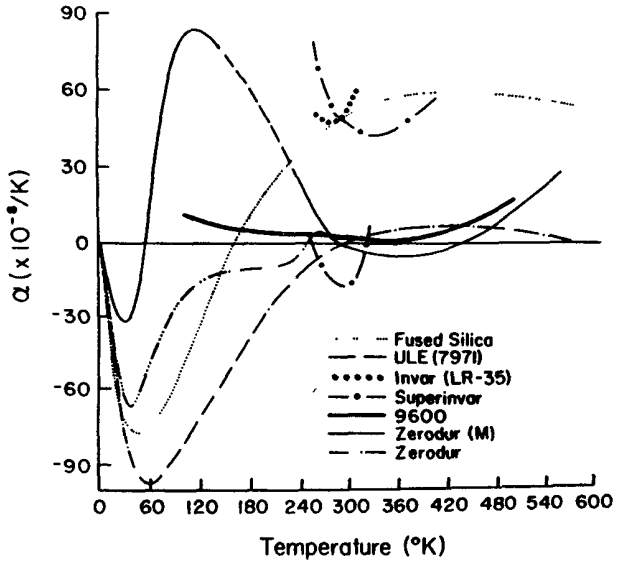

Figure 2. Thermal expansion coefficient versus temperature for some very low-expansivity materials.

3. THERMAL EXPANSION UNIFORMITY

While low expansivity is important to the performance of an optical system, the *uniformity of expansivity* is often even more important. Table II shows typical values of this parameter near room temperature. (The value for T08E fused silica applies through 100 K.)

Corning's ULE (Type 7971) is a material remarkable for its low expansivity near room temperature, for its low hysteresis (see Section IV), and for its excellent temporal stability (see Section V). Unfortunately, its method of fabrication results in a layering of expansivity, which must be carefully oriented with respect to the optical surface. (For example, the expansivity gradient must be normal to the optical surface.)

The recent development of new materials with improved properties, such as fused silica doped for enhanced thermal conductivity, can result in anisotropy, which can confuse measurers of expansivity. Figure 3 shows an example, where the expansivity of a cube-shaped sample was measured in three orthogonal directions.

Another interesting application of expansivity ansisotropy is strong carbon fiber, oriented along carbon's c-axis.[1] Figure 4 shows that the expansivity, -1 ppm/K, is the same as that of the bulk material in this direction.

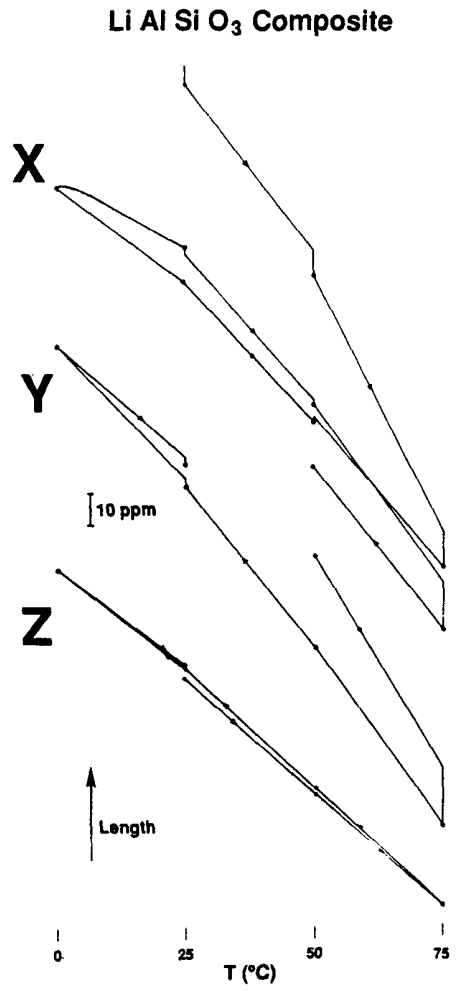

Figure 3. Anisotropic thermal expansivity of $LiAlSiO_3$.

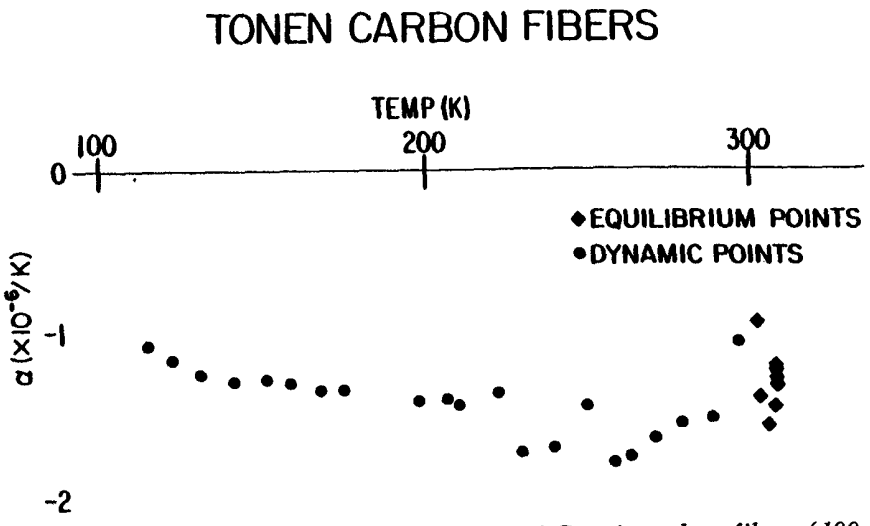

Figure 4. Thermal expansivity versus temperature of C-axis carbon fibers (100 to 300 K.)

Table II. Thermal expansion homogeneity.*

	Material	$\alpha_{300\ K}$ (ppm/K)	$\delta\alpha_{300\ K}$ (ppb/K)
1.	Aluminum 6061-T6	23.0	60 ?
2.	Beryllium VHP I-70A	11.5	130
3.	Beryllium HIP 1-70A	11.5	30 ?
4.	Borosilicate Schott Duran	3.2	30
5.	Borosilicate Ohara E-6	3.0	50
6.	Fused Quartz Heraeus Amersil T0iE	0.50	5
7.	Fused Silica Corning 7940	0.56	2.0
8.	ULE	0.03	4.0
9.	Glass Ceramic Schott Zerodur	0.05	40
10.	Cervit C-101	0.03	15
11.	Metal Matrix Composite AlSiCp ACMC SXA 24 30 v/o Si Cp	15	150

*Information provided by Daniel Vukobratovich.

4. THERMAL CYCLING HYSTERESIS

Thermal cycling hysteresis refers to a material's failure to return to its original dimensions after thermal cycling. Measurements of this hysteresis may be made in a number of ways. In the interest of saving time, one can slowly cycle or scan the sample temperature while continually monitoring the subsequent dimensional changes, assuming that thermal gradients across the sample remain negligible. Figures 5a and 5b show examples of thermal expansivity data obtained by the scanning method for quartz tubing. The discontinuities discovered here will be discussed in Section VII, but this example illustrates one source of measurement error.

Much more time consuming is the procedure of waiting until thermal equilibrium is reached before adjusting the temperature by the next increment. Although the error described above is generally less significant than the time saved, the scanning method fails to detect the "waiting time" required for the material to fully acclimate itself to the new temperature. For example, we find that materials like the glass-ceramics tend to very slowly "freeze up" as thermal equilibrium sets in, and then abruptly release pent-up energy at the onset of the temperature change. Figure 6 shows several examples of this for the glass-

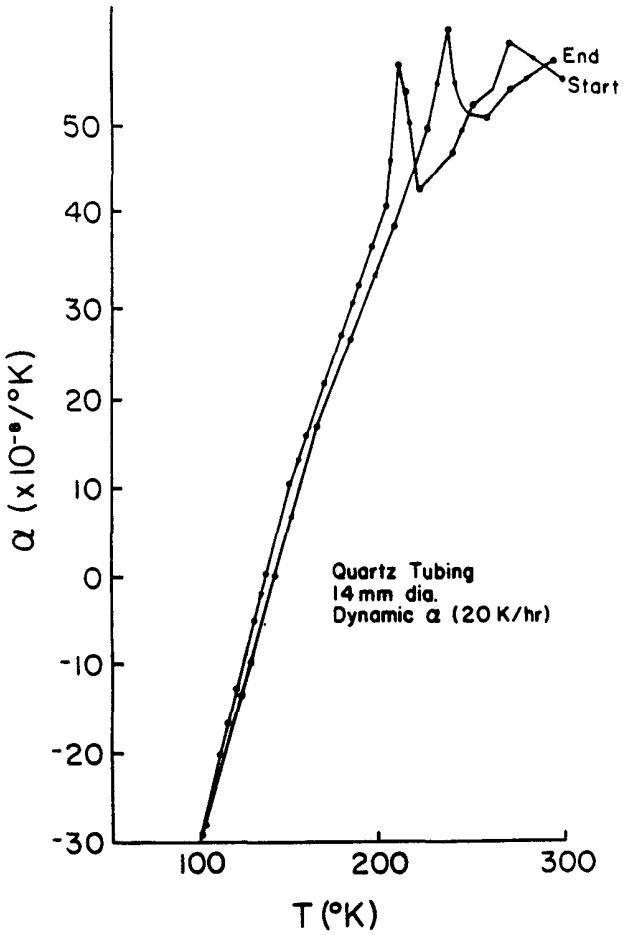

Figure 5. Thermal expansivity of fused silica tubing measured by scanning method.

ceramics tend to very slowly "freeze up" as thermal equilibrium sets in, and then abruptly release pent-up energy at the onset of the temperature change. Figure 6 shows several examples of this for the glass-ceramics Zerodur, Zerodur M, 9600, and V02.[2] Figure 7 shows data for Zerodur, including waiting times in hours. The criterion used here for thermal equilibrium was $\Delta L/L < 0.01$ ppm/hr for one hour. Note that, on occasion, it took as long as 2 days to satisfy that criterion, even with acid etch to relieve machining strains. In contrast, we have found ULE to be quite free of hysteresis effects (see Fig. 8).

It is appropriate to ask what effects hysteresis has on the performance of an optical system. In a recent investigation,[3] several ppm of hysteresis caused $\lambda/10$ figure distortion in 8-in. mirrors, but only when the mirrors were heated nonuniformly (for example, by infrared radiation from the back side). Under those conditions the mirror bowed during heating and did not fully regain its former shape upon cooling. This situation seems to be a real possibility in some space applications.

Another recent study was made to determine how important it is to relieve machining strains caused by hole drilling. In this case a 3/4-in.-diameter hole down the length of a 1 1/4 in. diameter rod was examined. Figure 9 shows cycling of Zerodur without acid etch after drilling. Figure 10 shows 9600 without acid etch.

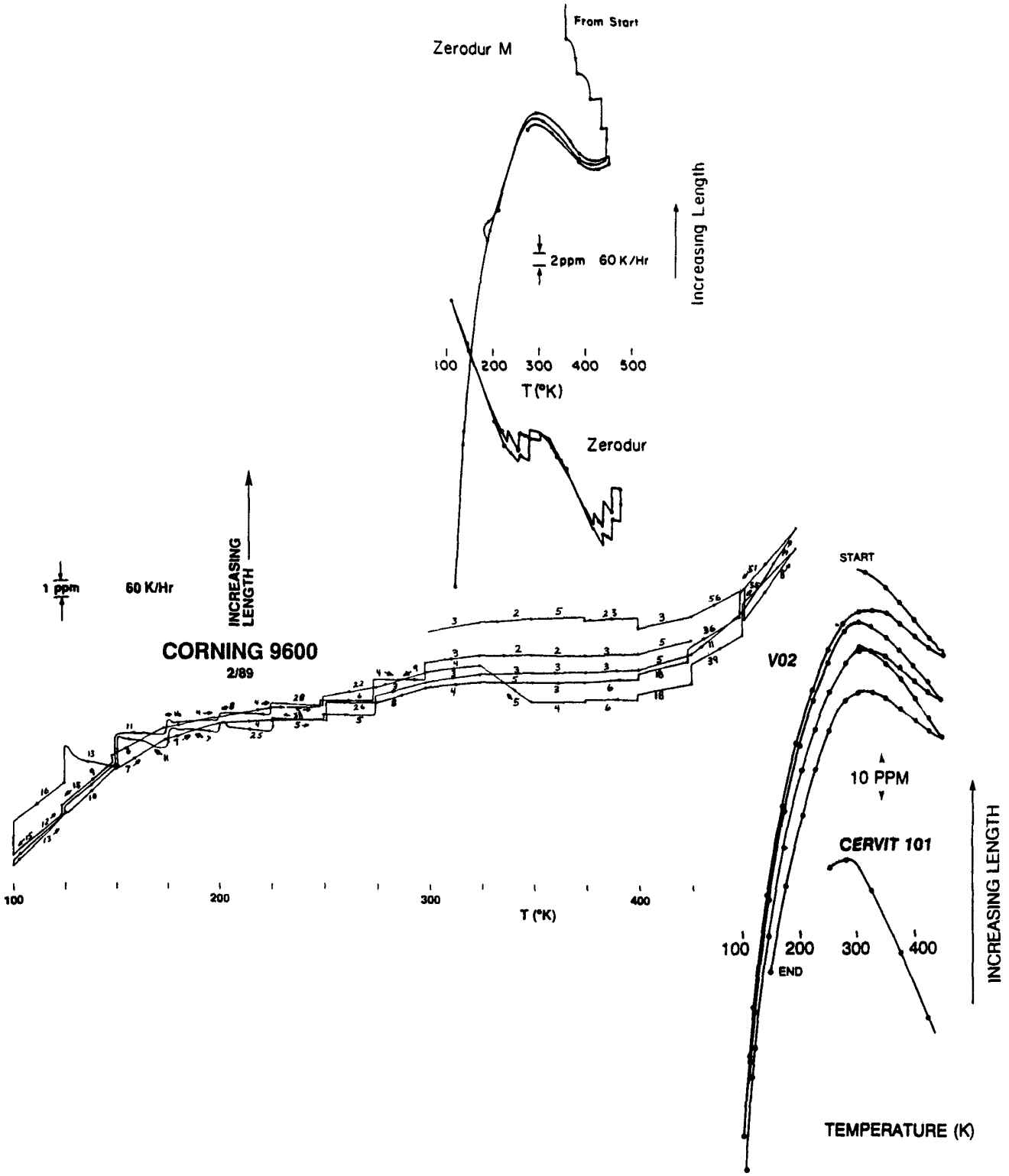

Figure 6. Thermal expansivity of (a) Zerodur and Zerodur M, (b) 9600, and (c) VO2.

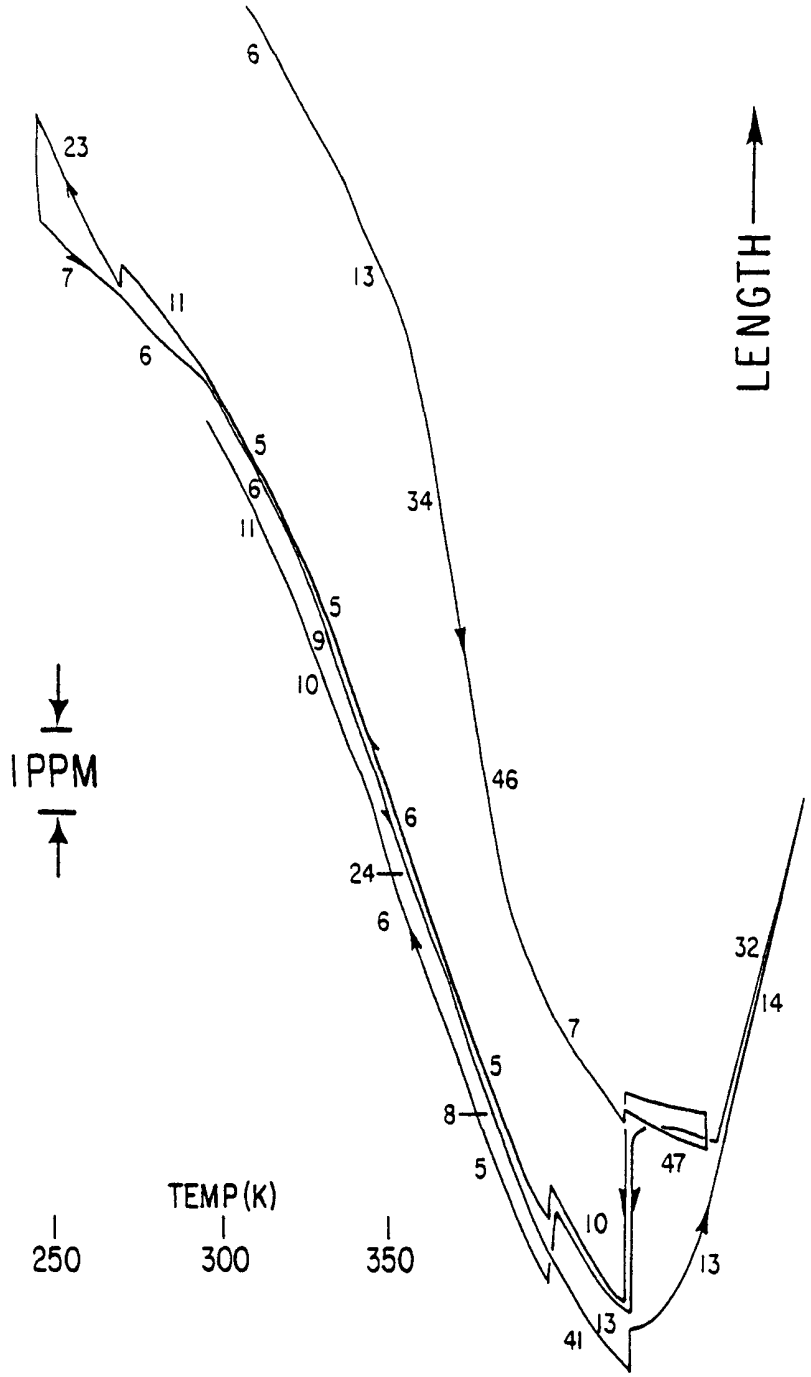

Figure 7. Thermal cycling of acid etched Zerodur, including waiting times in hours.

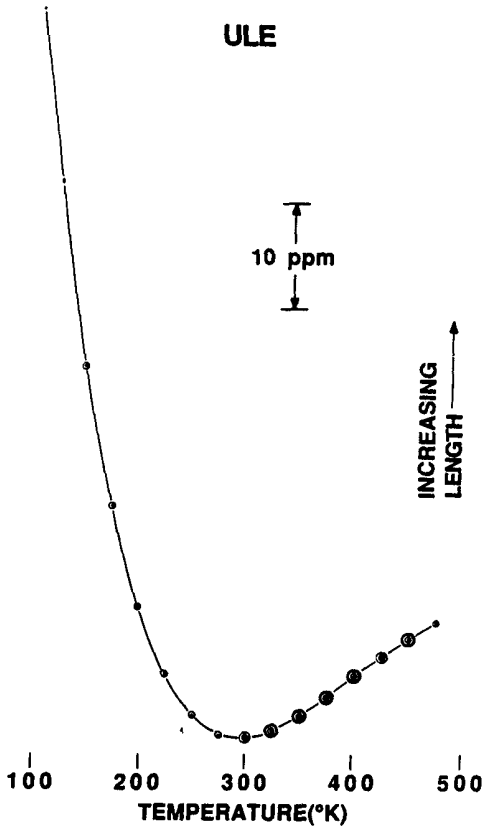

Figure 8. Thermal cycling of ULE.

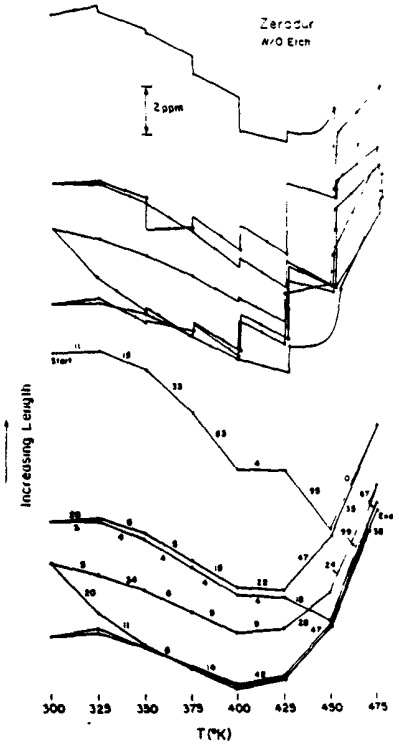

Figure 9. Effect of stress relief on thermal cycling hysteresis (Zerodur without acid etch).

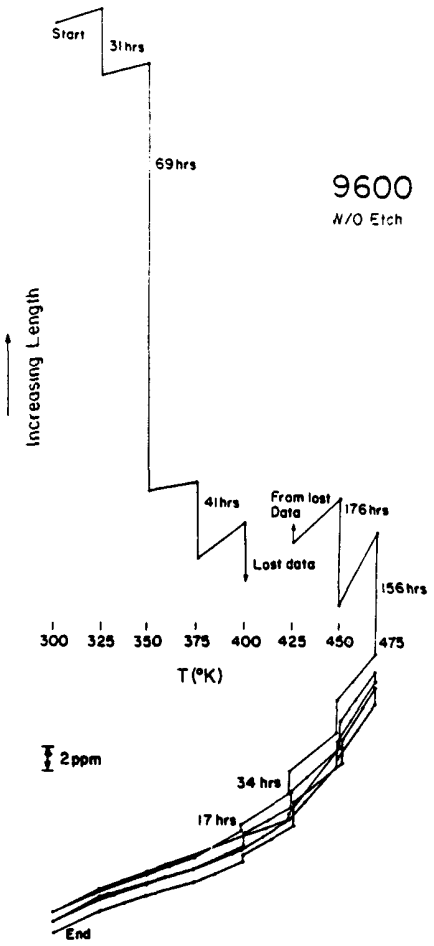

Figure 10. Effect of stress relief on thermal cycling hysteresis (9600 without acid etch).

5. TEMPORAL STABILITY

By temporal stability we mean a material's dimensional changes with time, at constant temperature and without external force applied to the sample. There is very little data on this material property,[4] with the prominent exception of Invars, which have been studied for over 50 years[5] gage blocks.[6] Invar's low thermal expansivity arises from the interplay between magnetic ordering and the normal lattice expansion with temperature increase. Invar's isothermal length change with time, however, can be as large as 0.1 ppm/day. As shown in *Physics and Applications of Invar Alloys*,[4] the elongation with time eventually halts, but this may take as long as 30 years. This period can be shortened considerably through use of heat treatments described by Schwab et al.[7] Figure 11 shows measurements of Invars with various heat treatments.

Because so little is known about temporal stability of materials, we were recently asked to use our high-sensitivity absolute method[8] to perform measurements for TRW, JPL, AiResearch, and Aerojet Corporation. These measurements are summarized in Table III and in Figures 12 through 26.

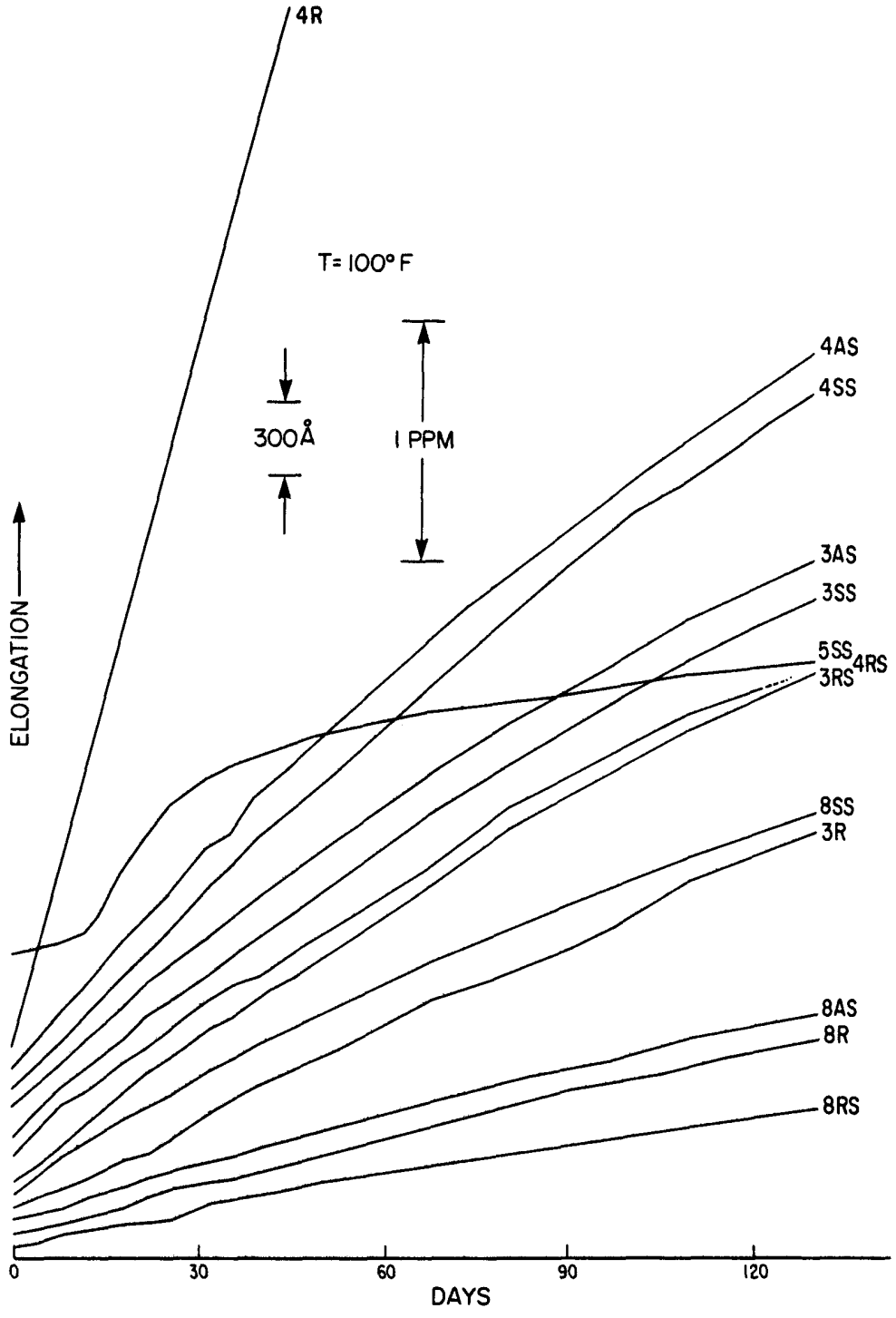

Figure 11. Temporal stability of Invars after various heat treatments.

Table III. Temporal stability of metal matrix composites and Al/Li alloys.

Supplier	Material	Heat Treatment	PPM/YR
ACMC	SXA ($AlSiC_p$)	see ACMC "Stabilization after Nickel Plating"	-1.23 -2.67 -5.42 -9.67
ACMC	SXA ($AlSiC_p$)	one cryocyle	-5.9 -4.3 -5.5 -7.2
DWA Composite	SiC Reinforced Al	one axial dunk LN_3 one axial dunk LN_3 (none) (none)	+2.20 ? +1.69 ?
DWA Composite	0.040" wall, 2-ply Liquid metal infiltrated 0.030" wall Graphite fiber	985°F/2 hr* (none) 985°F/2 hr* (none)	+6.50 -4.64 ? +7.12
Fiber Materials	Graphite fiber 35% Mg reinforced 2-ply (0°,90°)	LN_2 axial quench (none) (none)	+19.8 +14.7 +20.3 +11.9
Fiber Materials	Graphite Fiber Aℓ 48% 2-ply (0°)	(none) " " "	-2.56 -3.52 -3.07 -6.55
INCO LIGHT MATERIALS	AℓLiMg MAP Al-905 XL Forged air frame Backup Fitting	325°F 2 hr air cooled (none) 10/22/89 "	-21.8 -18.3 -76.4 -35.3

*Water quench, then heat to 320°F/1 hr; air cool.

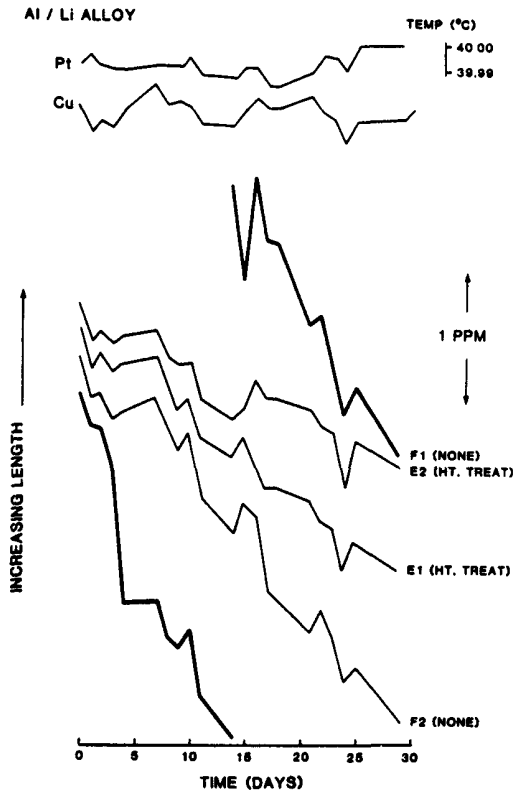

Figure 12. Temporal stability of aluminum/lithium alloy.

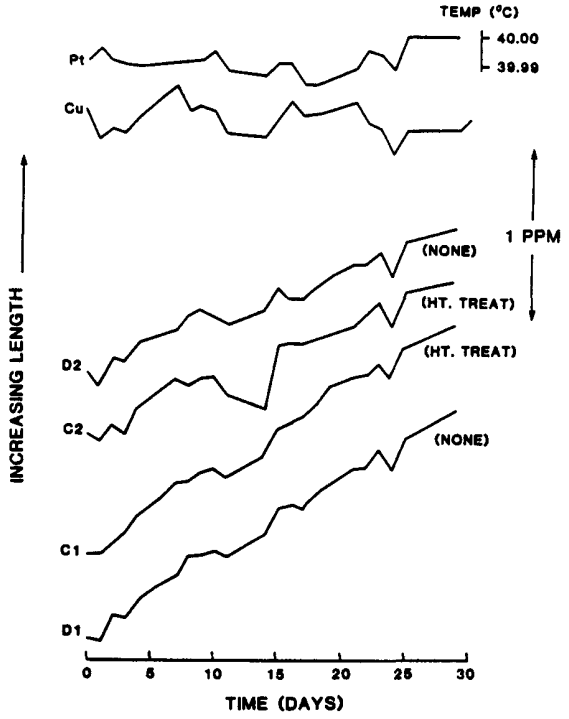

Figure 13. Temporal stability of graphite fiber reinforced Mg.

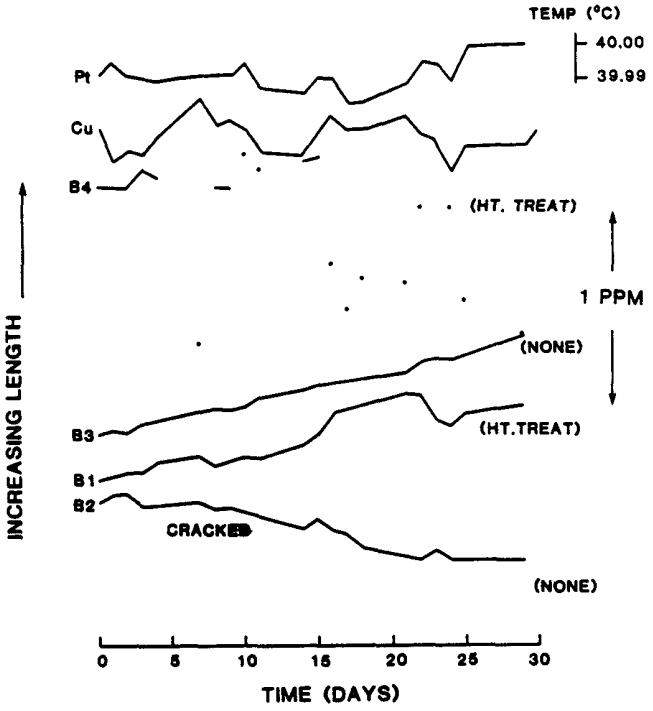

Figure 14. Temporal stability of graphite fiber reinforced Al.

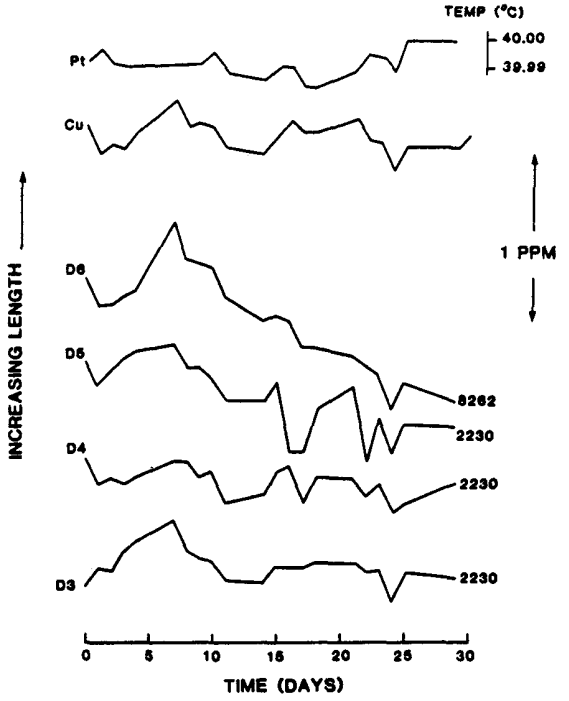

Figure 15. Temporal stability of metal matrix composite $AlSiC_p$ (cryocycled 5X).

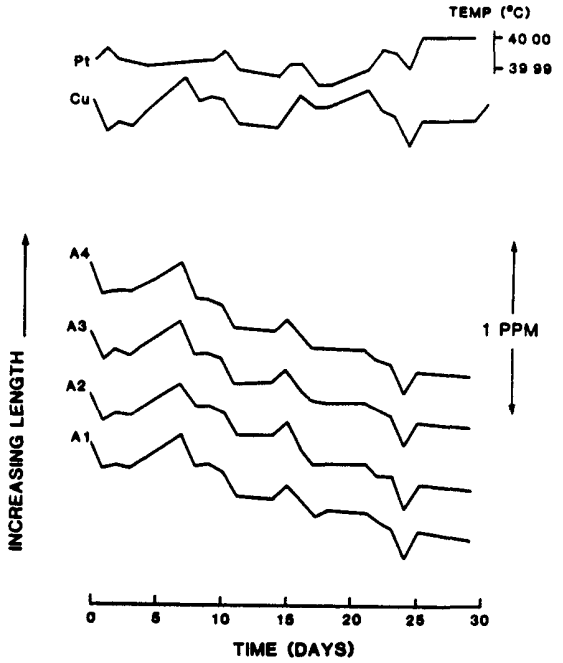

Figure 16. Temporal stability of metal matrix composite $AlSiC_p$ (cryocycled 1X).

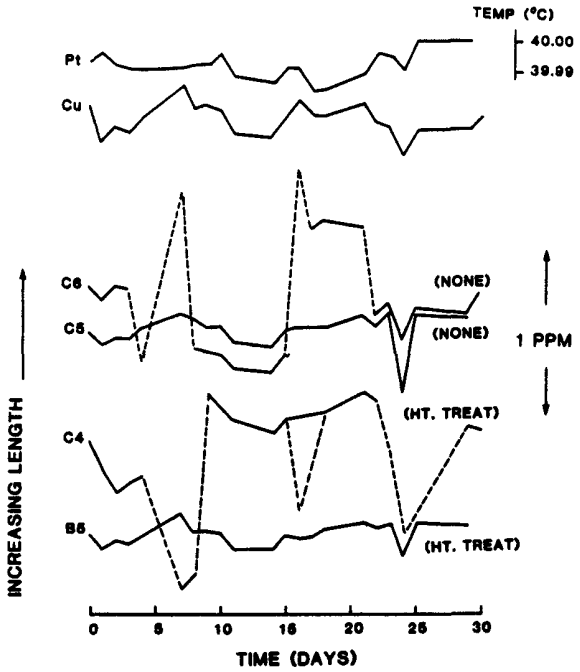

Figure 17. Temporal stability of metal matrix composite $AlSiC_p$ (cryocycled 5X).

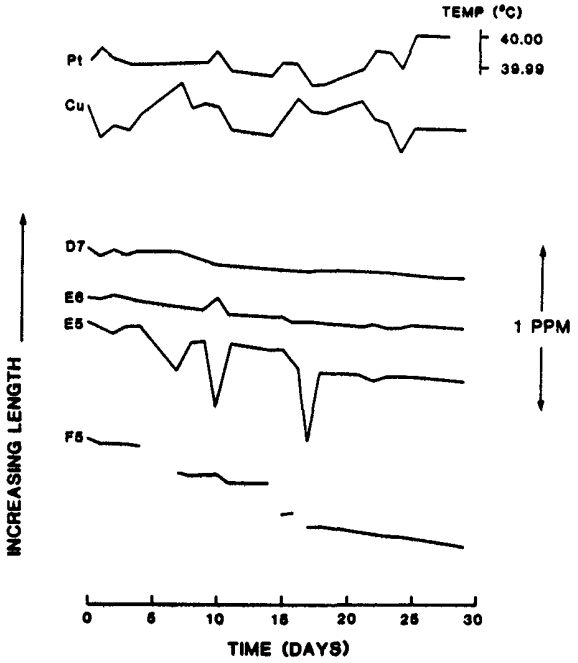

Figure 18. Temporal stability of graphite fiber reinforced aluminum.

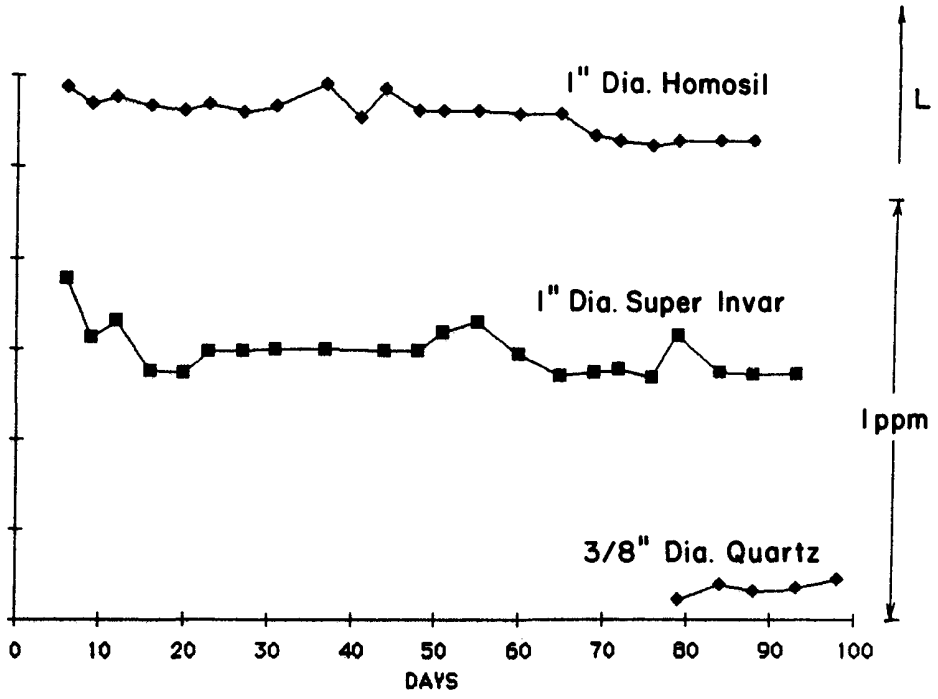

Figure 19. Temporal stability of fused silica and superInvar.

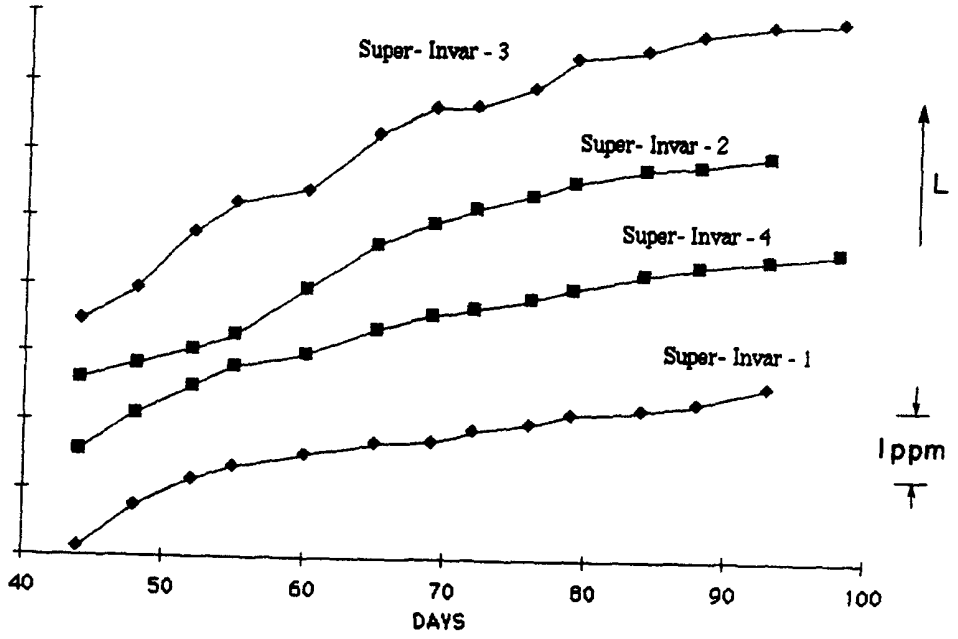

Figure 20. Temporal stability of superInvars.

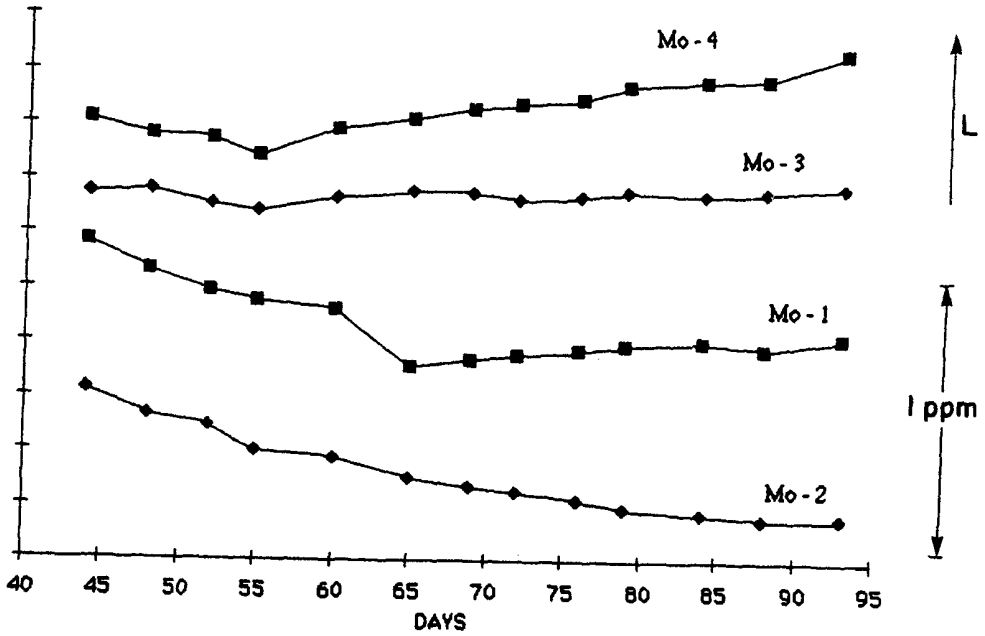

Figure 21. Temporal stability of molybdenum.

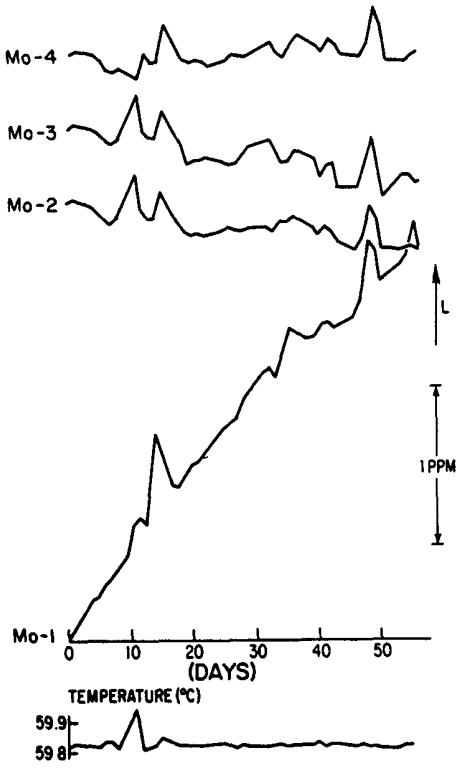

Figure 22. Temporal stability of molybdenum.

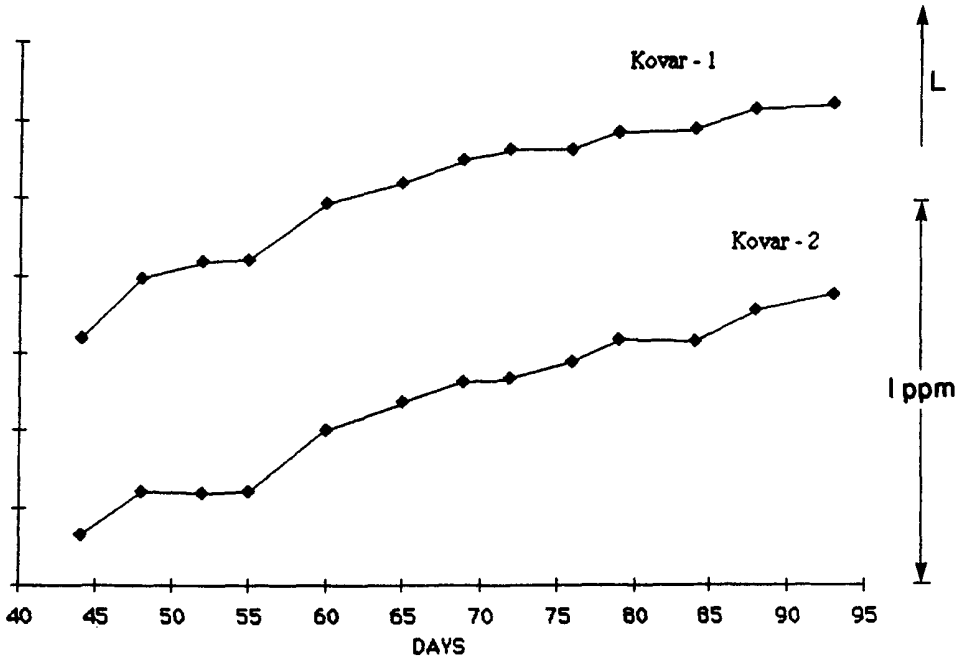

Figure 23. Temporal stability of kovar.

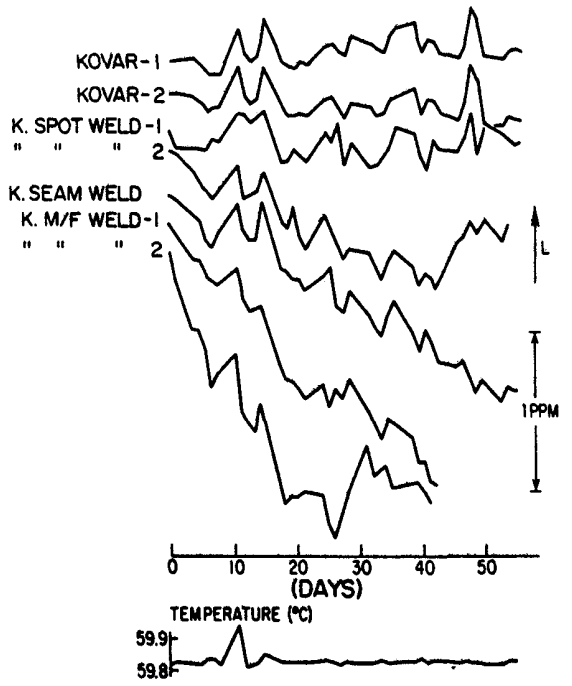

Figure 24. Temporal stability of kovar welded joints.

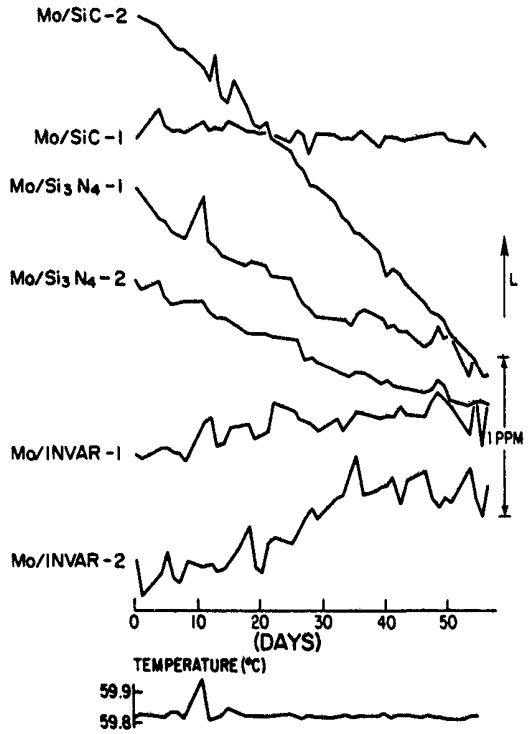

Figure 25. Temporal stability of molybdenum joints.

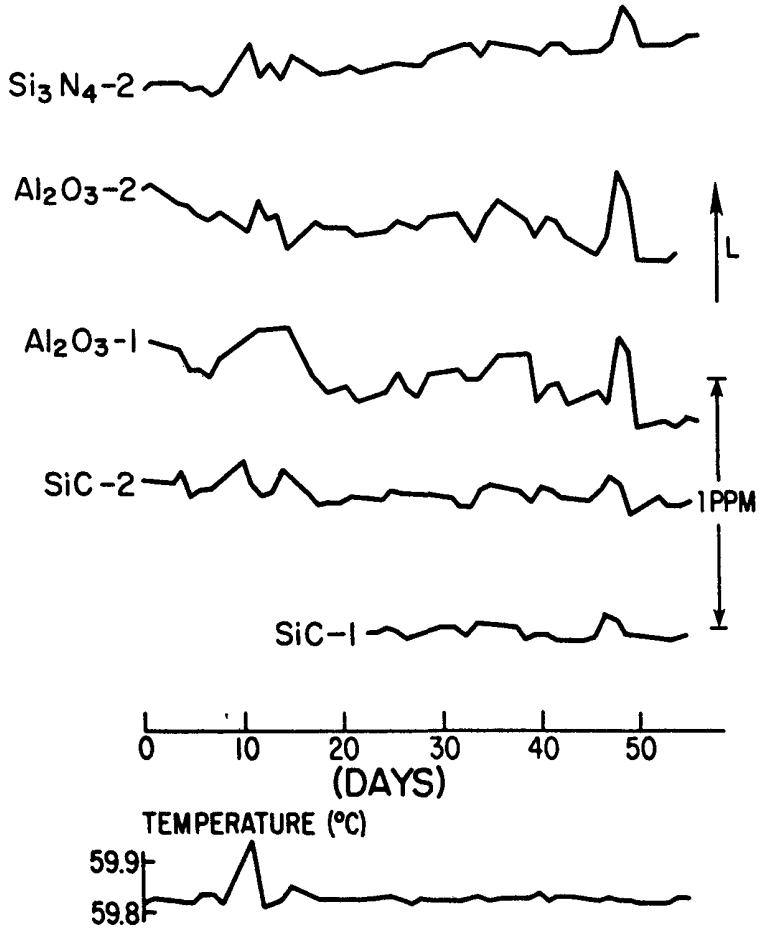

Figure 26. Temporal stability of SiC, Si_3N_4, and Al_2O_3.

Which are the most stable materials? In practice these will be materials that exhibit both excellent temporal stability and low thermal expansivity. The best measurements I know of involve optical cavities formed using optical contacts. These cavities have been measured to shrink approximately their rms roughness in half a year.[4] J. Hall[9] reports a 30-cm long ULE cavity whose stability near room temperature was 0.1 Hz/sec. Because $\Delta L/L = \Delta\nu/\nu$, this implies a shrinkage of 6 ppb/yr, much of which was attributable to shrinkage of the optical contacts.

6. GAMMA IRRADIATION

Our experience in this area is limited to the glass-ceramic CER-VIT 101. When quartz is irradiated by gamma rays, point defects, including color centers, are formed, and the bulk material is found to compact.[10] This behavior seems consistent with the changes we observed in CER-VIT. Figure 27 shows CER-VIT 101 thermally cycled (a) before and (b) after irradiation by ^{130}Cs gamma rays with a dosage of 10^5 rads/hr for 37 hours. On irradiation the sample turned black. Figure 27b shows that heating after irradiation resulted in expansion of about 100 ppm. In addition, the sample returned to its original color, indicating that the radiation effects were largely reversible upon heating. Note that the material's "reorganization times" tend to become greater as the temperature rises. After cooling, the material showed no significant hysteresis nor other changes from its behavior before irradiation.

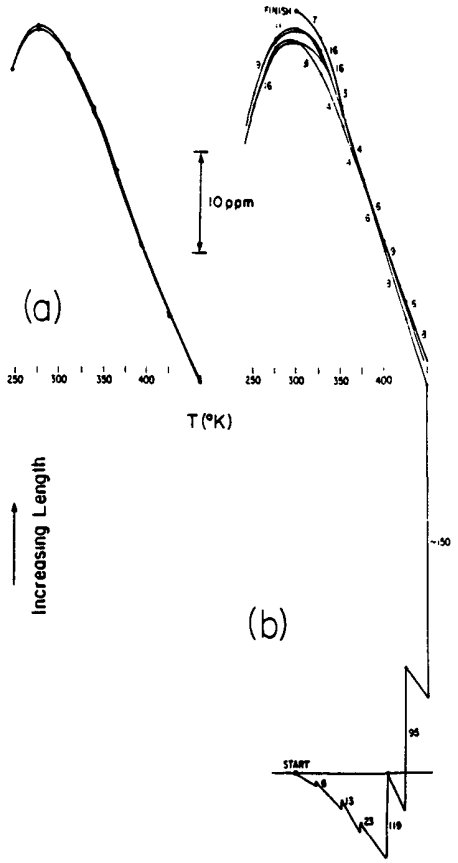

Figure 27. Effect of gamma irradiation on thermal expansion cycling of CER-VIT 101.

7. MISCELLANEOUS PROBLEMS

7.1 Cyrogenic Glitch

We have repeatedly encountered erratic dimensional behavior in fused silica, glass-ceramics and sol-gels in the temperature range 200 - 250 K. This erratic behavior seems to indicate some sort of phase change in the material. We have come to associate this behavior with SiO_2, since all these materials contain SiO_2. The erratic behavior seems not to be inevitable, but its occurrence is sufficiently widespread that it deserves mention.

We encountered a dramatic case of such behavior during an investigation to determine the thermal expansion uniformity of well-annealed fused silica tubing used to support lightweight mirrors (see Fig. 28). We found that adjacent samples of production tubing were so different in the 200-250 K range that we were unable to use our differential expansion technique.[11] Quick survey scans (Fig. 5) showed what was taking place. We therefore remeasured our samples (14, 18, and 25 mm diameter tubing), waiting for thermal equilibrium at 25-degree Kelvin increments. Results for the 25-mm tubing are shown in Fig. 29. We checked the anneal of the fused silica and found it to be quite good (stress-induced birefringence was about 5 nm/cm). Another example of this problem recurred with an experimental Sol-gel (see Figs. 30, 31). Better material, presumably better annealed, did not exhibit this problem.

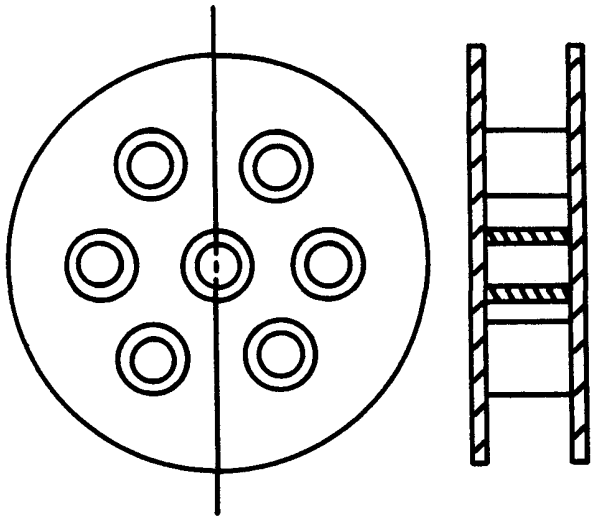

Figure 28. Lightweight mirror configuration using fused silica tubing to space front and back plates.

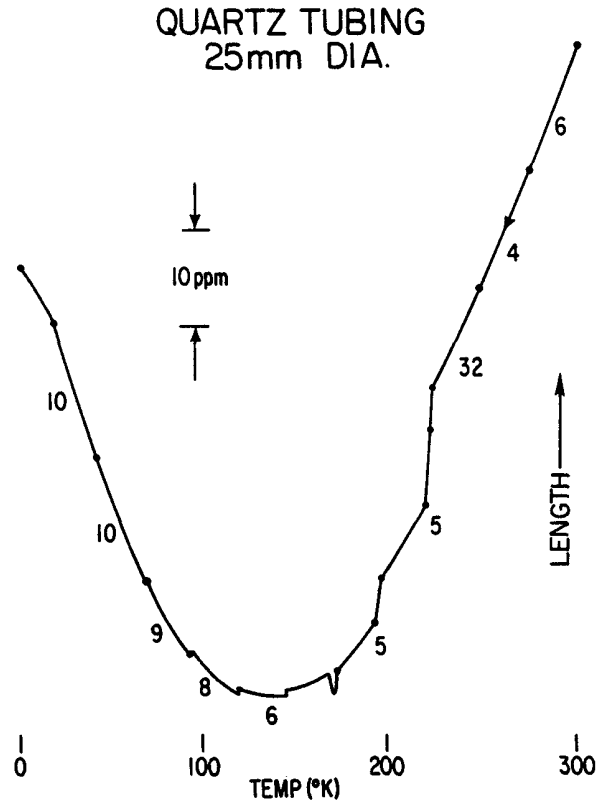

Figure 29. Fused silica tubing expansion versus temperature measured waiting for thermal equilibria.

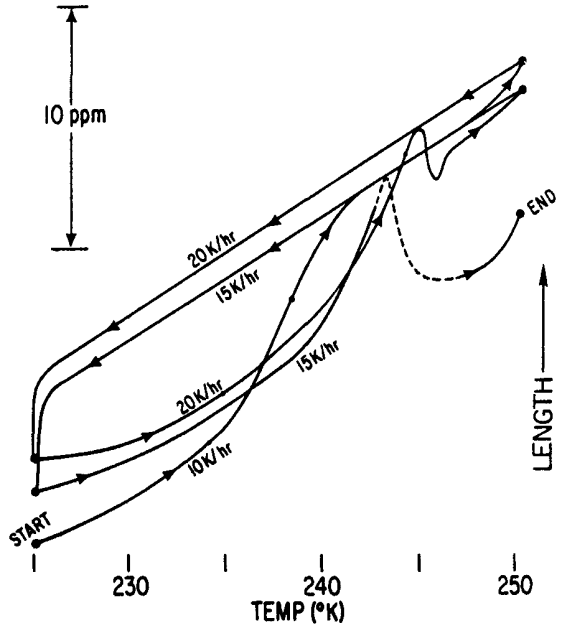

Figure 30. Erratic behavior of sol gel thermally cycled near 240 K.

In evaluating the development of Zerodur and Corning 9600, we also noted problems in the region from 200 to 250 K (see Figures 6a, b, and c). Apparently the glassmaking experts know how to cope with these problems after they surface, but because this temperature region is becoming more and more important in space applications, we should work to understand the problem. This consideration is especially important for a material as widely used as fused silica.

7.2 The Search for a Strong and Stable Material

The dimensional stability tradeoffs between Invar (Fe/Ni) and Superinvar (Fe/Ni/Co) are rather complicated. Presumably, we are interested in low thermal expansivity, but over what temperature range? What about temporal stability? And what about cold working (springiness)?

If we assume our applications don't require springiness, then Superinvar with appropriate heat treatment can offer a factor of three to four lower expansivity than can regular Invar over the temperature range -20 to 120°C. Note that the curves shown in Fig. 2 illustrate only typical cases.

One special problem with Superinvar is that it must never be allowed to cool below its phase-transition temperature, which Carpenter Steel can guarantee to keep below -55°C.

With regard to temporal stability of wires and tapes, G. Girard of B.I.P.M. has achieved excellent results[12] (α < 1 ppm/K and temporal stability < 1 ppm/yr). For bulk material, however, this performance is not yet readily obtainable. We have measured some Superinvar with parameters equally good at 27°C, but we found its temporal stability degraded at 40°C to +2ppm/yr. Clearly, a complicated interplay of factors is at work, and thus far the demand has not justified sufficient effort, especially in the area of temporal stability.

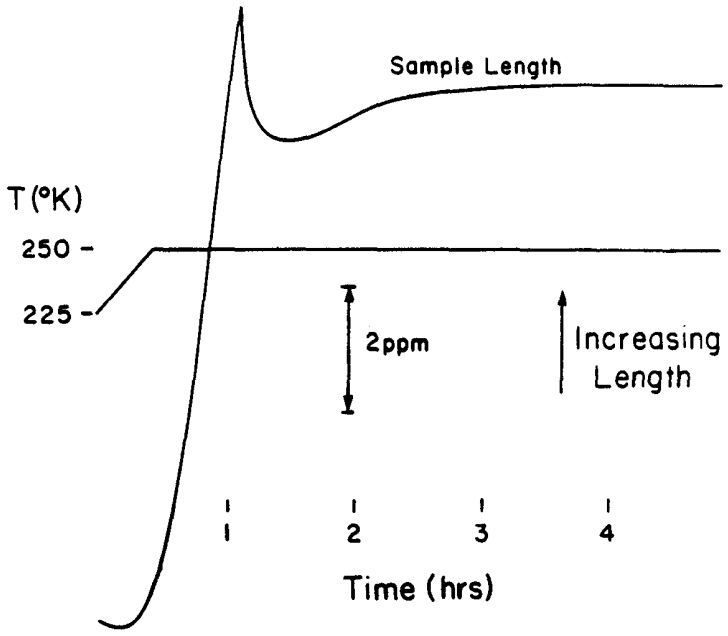

Figure 31. Sol gel length change versus time as temperature rises through the 240 K region.

Efforts to make a very stable metal have been ongoing for more than a hundred years. Because it is such a difficult problem, alternate materials, such as graphite/epoxy, have been developed over the past fifteen years. These materials offer other advantages as well. They are very attractive from a weight, strength, and thermal-expansion standpoint. They do have problems with dimensional stability upon thermal cycling and exposure to moisture, but these problems are becoming better understood. Assuming those factors can be controlled for these materials, we still must learn about their temporal stability, a property about which almost nothing is now known. In this case, the demand for this information will very likely justify the effort.

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