(YPS)

SEGMENTED HIGH AVERAGE POWER Ho^{3+}:YLF LASER

Semi-Annual Report No.1

Period Covered: 8 November 1971 - 16 June 1972

Contract No.: N00014-72-c-0137
Expiration Date: 31 December 1972
Amount of Contract: $82,353

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Program Code No. 421

SANDERS ASSOCIATES, INC.
ELECTRO-OPTICS DIVISION
95 Canal Street - Nashua, New Hampshire 03060

incipal Investigator: William C. Fricke
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13. ABSTRACT

A novel technique for building disk lasers is described which offers considerable simplification of their design. The laser disk is bonded into a glass Holding ring with Teflon FEP film. Tapering the mating surfaces of the disk and disk holder not only makes assembly possible but also minimizes the effects of different thermal expansion coefficients of the two pieces. Calculations of the maximum fabrication errors and bonding pressures indicated that the technique was, indeed, feasible. A Ho^{3+}:$LiYF_4$ disk was bonded into a glass slide, verifying these preliminary calculations. Measurements of the transmittance of the bonded surfaces indicate that a very low loss interface is formed due to the nearly equal indicies of refraction of the Teflon film and glass or $LiYF_4$.

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A novel technique for building disk lasers is described which offers considerable simplification of their design. The laser disk is bonded into a glass holding ring with Teflon FEP film. Tapering the mating surfaces of the disk and disk holder not only makes assembly possible but also minimizes the effects of different thermal expansion coefficients of the two pieces. Calculations of the maximum fabrication errors and bonding pressures indicated that the technique was, indeed, feasible. A Ho^{3+}:$LiYF_4$ disk was bonded into a glass slide, verifying these preliminary calculations. Measurements of the transmittance of the bonded surfaces indicate that a very low loss interface is formed due to the nearly equal indicies of refraction of the Teflon film and glass or $LiYF_4$.

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TECHNICAL REPORT SUMMARY

A summary of the work performed on the "Disk Design for Segmented High Average Power Ho^{3+}:YLF Laser" program Contract No. N00014-72-c-0137 is presented below. The goal of this part of the program is the demonstration of the use of FEP Teflon as a bonding agent between the disks of a segmented Ho^{3+}:YLF laser and the individual disk holders. A disk laser will be built under this contract employing the above technology to verify the expected operational improvements of such a laser using the disk-holder assembly building blocks. It is expected that this approach will lead to the elimination of stress induced polarization rotation and "edge" effects from radial heat transfer to the circumference of the disk and result in an undistorted beam for high average power crystalline lasers. In addition, this technique will permit the laser designer more latitude in selecting different material properties for the disk holder since he is not required to match the coefficient of expansion of the laser disk and laser disk holder materials.

Initial bonding experiments were simulated utilizing glass disks in glass rings as a preliminary to bonding a Ho^{3+}:YLF disk in a glass disk holder. By tapering both the disk and disk holder slightly on their mating circumference it was determined that the effects of the difference in the coefficient of expansion of the materials in the disk and disk holder can be minimized. These tests have been quite successful resulting in a bond which is stronger than the glass/glass assembly. Furthermore, the transmission through the two bonded surfaces has been measured to be greater than 90% and limited by the reflection losses.

Further bonding experiments with YLF have been equally successful. The YLF crystal withstood the heating and cooling cycle required for the bonding process with no signs of damage and residual stress whatever.

The two aspects of this program which have been essentially completed are:

1) The design of the disk laser, and
2) The development of a technique for bonding the disks into the disk holder.

Calculations leading to the design of the Ho^{3+}:YLF laser are being performed in regard to the following items:

1) Pump lamps and expected pumping rates
2) Disk dimensions
3) Cooling and related problems
4) Pump cavity design
5) Gain and output power density
6) Ho:YLF disk amplifier design

Due to the complicated interaction of Erbium, Thulium and Holmium in this laser material, only the maximum and minimum values of the optimum doping concentration are being calculated. Therefore the above design parameters are being calculated on the basis of a doping concentration which fell between these two limits.

1.0 INTRODUCTION

One of the important problems of this program was to find a technique to bond the disk to the inside of the disk holder using Teflon as the adhesive. A solution to this problem is the topic of this report.

We shall begin by discussing the technique for bonding with Teflon FEP film. The particular technique for bonding the YLF disks will then be presented. Calculations of the required disk shape and ring material parameters are given as well as the results of an experiment where a YLF disk is bonded into glass slide.

2.0 BONDING WITH TEFLON FEP FILM

Bonding with Teflon is actually a straightforward process for flat surfaces. A piece of Teflon film is simply placed between the two surfaces (Figure 2.1). The two plates are heated and pressed together. The temperature of the plates must be high enough to melt the Teflon (550°F) and the pressure high enough (~ 100 PSI) to force the melted Teflon into the surface of the plates. Once this combination has been achieved, the plates can be cooled and the bond is complete.

Bonding of a YLF disk into a holding ring requires provision for establishment of a diametral pressure between the two components. Normal "shrink-fit" techniques, that use the thermal expansion of the materials by differential heating or because of different values of thermal expansion, is inappropriate for this application because of the small gap that could be provided. A small taper on the mating surfaces, however, will permit assembly of the disk by axial loading during heating (see Figure 2.2). This permits the bonding pressure (normal to

BONDIN [illegible] TEFLON FEP FILM

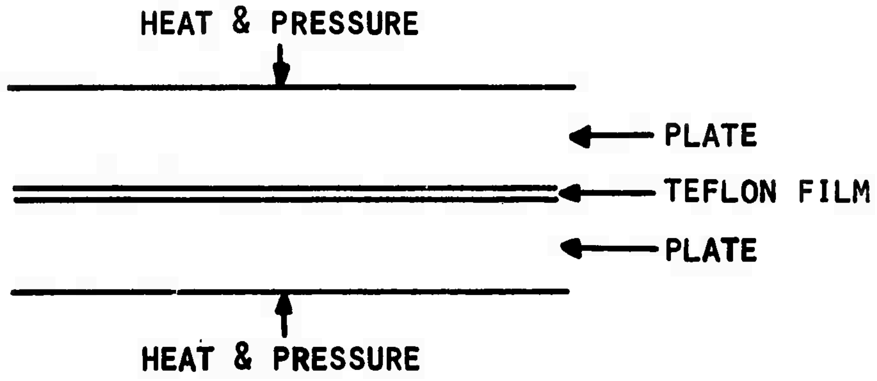


Figure 2.1

TECHNIQUE FOR BONDING THE YLF DISK INTO A HOLDING RING

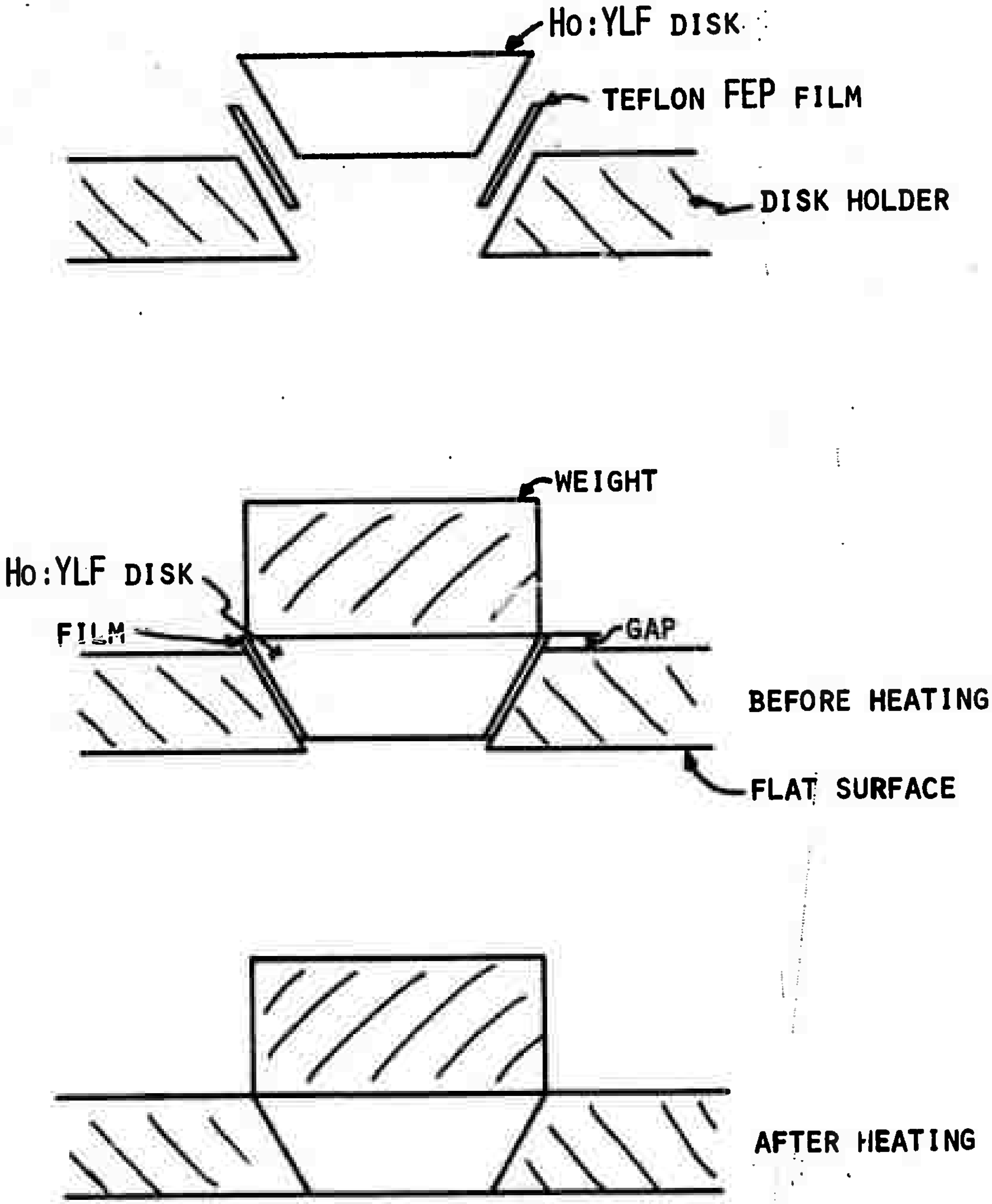


Figure 2.2

the surface of the disk) to be produced by merely pushing the disk into the holding ring. As will be shown below, a weight of under five pounds is sufficient to produce the required bonding pressures normal to the conical surfaces. The radii of the disk and ring should allow some room for the two to settle together as they are heated.

The advantages of this technique are:

1) Problems associated with thermal expansion are eliminated, since the Teflon is soft and will deform and flow under pressure;

2) An easily controllable bonding pressure can be applied during heating and cooling of the assembly;

3) The tolerances of the radii and cone angle of the disk and ring are not too stringent, as the Teflon film will flow when melted and will fill in places where the disk and ring do not conform well to each other.

The disadvantages are limited only to fabrication of the two matching conical surfaces.

3.0 FABRICATION TOLERANCES AND PROCEDURES

Fabrication tolerances for the ring and disk are estimated below. Three tolerances are discussed:

1) The mismatch of the cone angles of the holding and the disk;

2) The maximum error in the radii and their effect on the final assembly;

3) The maximum thermal expansion which the teflon can accommodate before undue stress or breakage of either the disk or ring occurs.

Finally, suggestions for fabrication of a disk/ring assembly are presented which should assure a good fit.

3.1 MAXIMUM ANGULAR MISMATCH OF CONES

Assuming the radii at one end of the disk/ring assembly are cut properly, the maximum angular mismatch can be estimated by setting the thickness change (due to thermal expansion) of the Teflon during the heat bonding process, δ, equal to the gap created at the other side of the disk (see Figure 3.1).

Thus

$$\Delta\theta = \frac{g \cos\theta}{h \sec\theta} = \frac{\delta}{h \sec\theta} .$$

If t is the thickness of the film, then, since the total lineal expansion of the film upon heating from 50°F to 550°F is about 10% (see Figure 3.2).

$$\delta \approx 0.1\ t$$

For small angles,

$$\Delta\theta \approx \frac{0.1\ t}{h} .$$

A ten mil thick film will be able to accommodate an angular mismatch of

$$\Delta\theta \simeq 0.6° .$$

ANGULAR MISMATCH OF THE CONE ANGLES

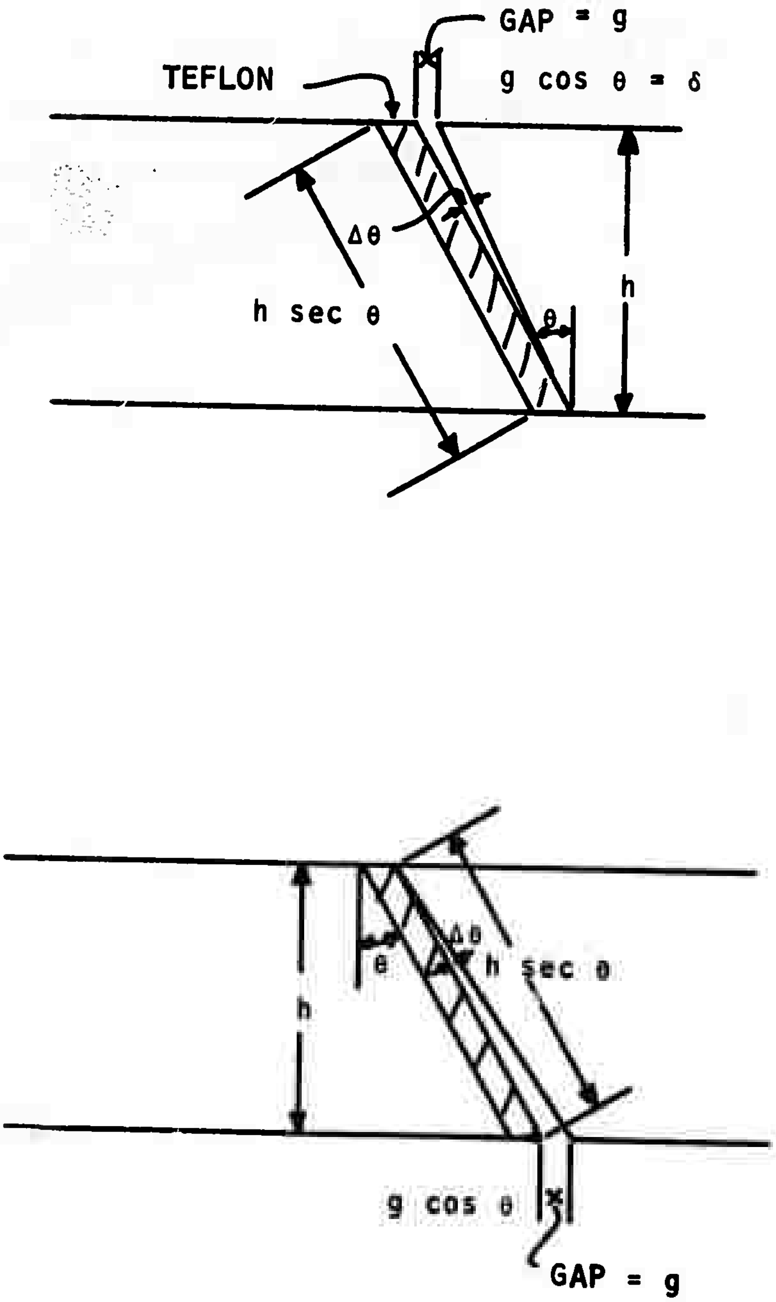
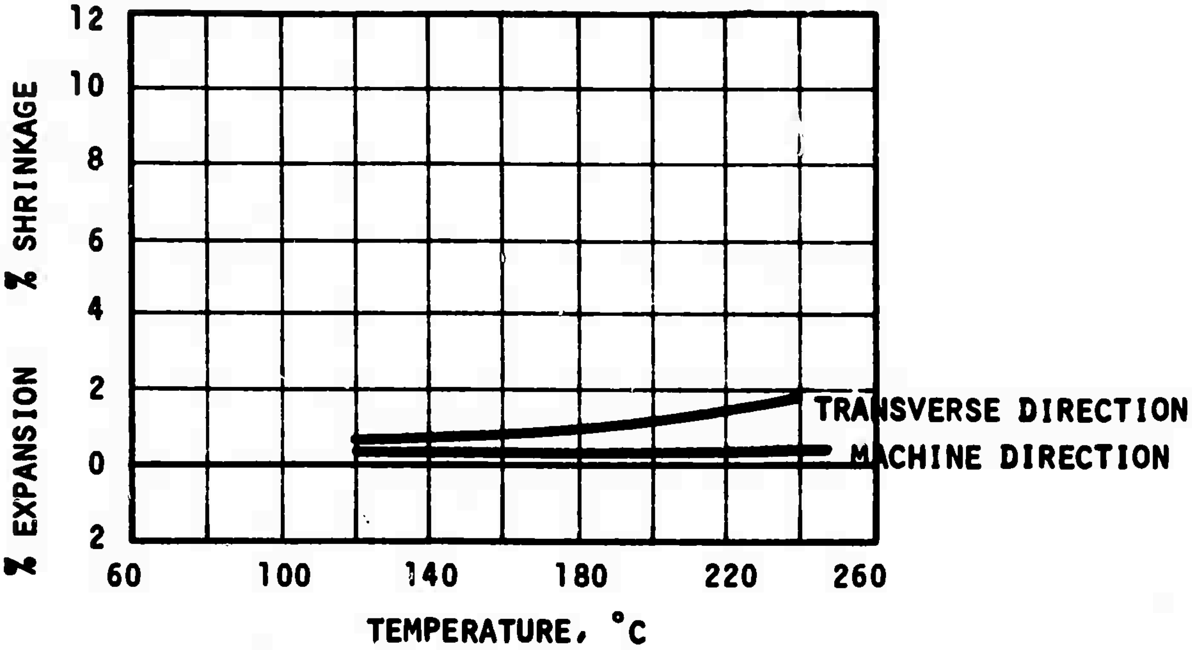
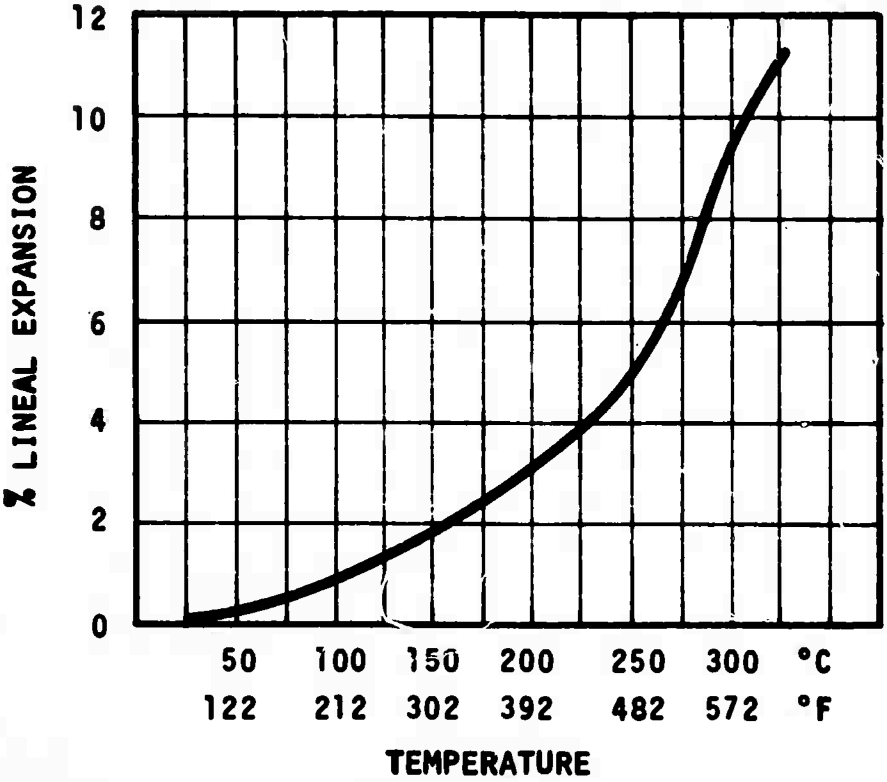


Figure 3.1



SHRINKAGE Vs. TEMPERATURE*

500 "TEFLON" A



THERMAL EXPANSION*

Figure 3.2

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* FROM REF. (8)

Since the cone angles can be lapped together to an angle closer than 0.6°, the Teflon will certainly be able to take up any mismatch which should occur.

3.2 MAXIMUM ERROR IN RADIUS

Assuming now that the cone angles are equal, the maximum error in the radii of the disk and ring is simply (Figure 3.3)

$$\Delta r = \Delta h \tan \theta .$$

Presumably a maximum tolerable value for Δh can be determined from cooling considerations where an edge might cause a stagnant pocket of coolant over the disk. It should be noted that the radii must be made fairly accurately since $\tan \theta << 1$ and Δh is small. If, $\Delta h = 0.01\text{cm}$, then

$$\Delta r \approx 10^{-4}\text{cm}$$

It might be easier to repolish the YLF disk/ring assembly after bonding to assure a small Δh.

MAXIMUM ERROR IN THE RADII OF THE DISK AND HOLDING RING

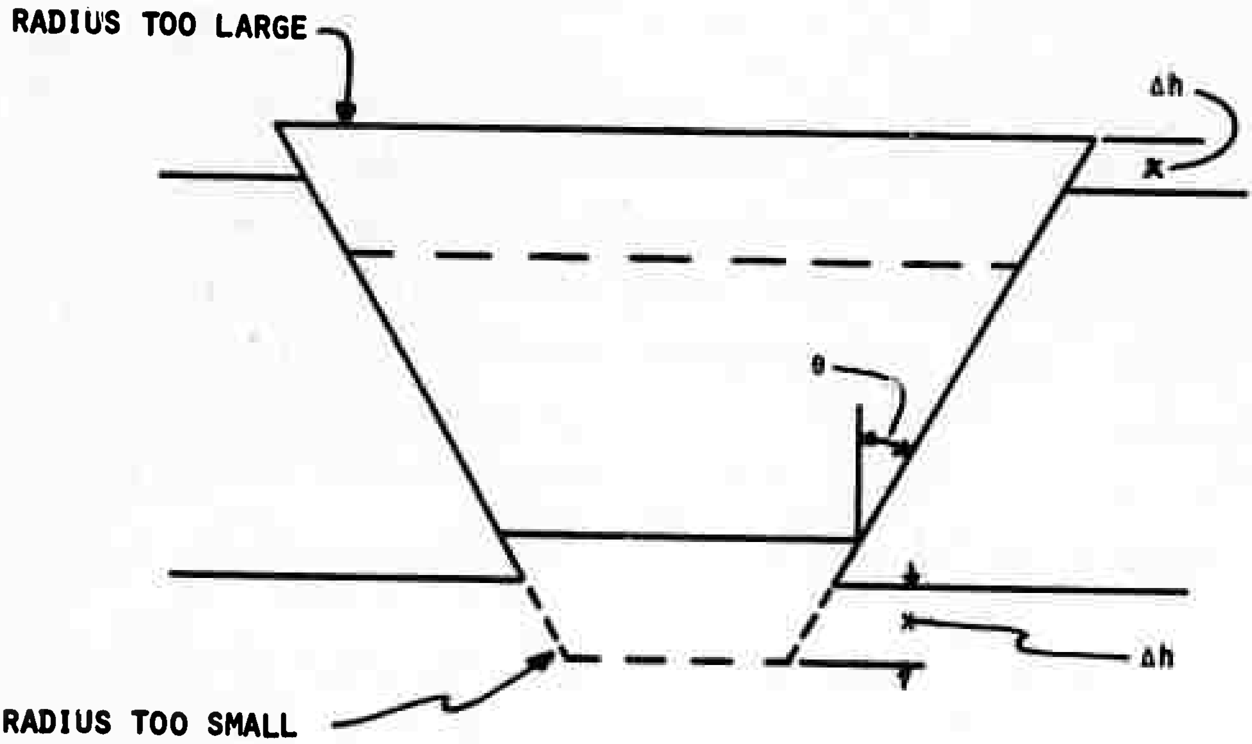


Figure 3.3

3.3 THERMAL EXPANSION CONSIDERATIONS

Thermal expansion poses a potential problem since the YLF disk/glass ring assembly must be heated to around 550°F to melt the Teflon film. The film, however, can act as a buffer between the disk and the ring which will prevent breakage of either element. The change in radius of the YLF disk and the glass holding ring is computed below for a temperature excursion of 550°F.

The gap between the disk and the ring (which is filled with Teflon) has a width (see Figure 3.4)

$$g_o = R_{r1} - r_{d2} = t' \sec \theta$$

at room temperature. At elevated temperatures

$$g = (R_{r1}\alpha_{Tr} - r_{d1}\alpha_{Td})\Delta T + g_o$$

DEFINITION OF DISK PARAMETERS USED IN THE CALCULATIONS

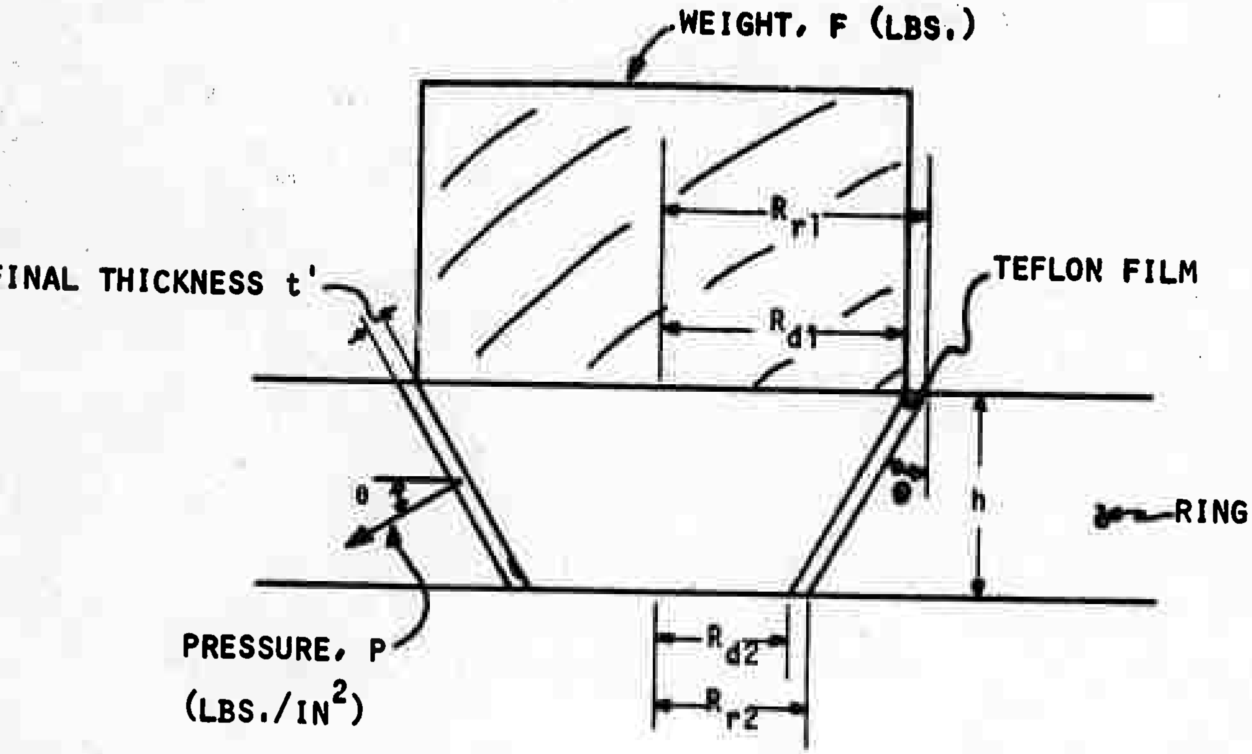


Figure 3.4

where α_{Tr} is the thermal expansion coefficient for the ring ("r") and α_{Td} is the thermal expansion coefficient for the disk ("d"). Since

$$R_{r1} = r_{d1} + g_o$$

at room temperature.

Then

$$g = r_{d1}(\alpha_{Tr} - \alpha_{Td})\Delta T + g_o(1 + \alpha_{Tr}\Delta T)$$

at elevated temperatures. The change in the gap width with temperature is, therefore,

$$\frac{\Delta g}{\Delta T} = \frac{g - g_o}{\Delta T} = r_{d1}(\alpha_{Tr} - \alpha_{Td}) + g_o\alpha_{Tr}.$$

The Teflon film has even more pronounced thermal expansion characteristics than either the ring or the disk. At 550°F it will have expanded to about 111%[*] of its room temperature thickness. Such thermal expansion can only be observed after the

---

[*] See Figure 3.2

residual shrinkage of the material has been removed. When Teflon film is heated and cooled for the first time residual shrinkage occurs. This shrinkage happens because stresses, established inside the film during its manufacture, are removed. Once residual shrinkage has been removed, the normal thermal expansion properties of the film allow its expansion and contraction with temperature to be computed.

When the Teflon film has its residual shrinkage removed, its thermal expansion coefficient, α_{TT}, is, approximately,

$$\alpha_{TT} = 330 \times 10^{-6}/°C.$$

3.4 RESIDUAL STRESS ON ROOM TEMPERATURE BONDED DISK

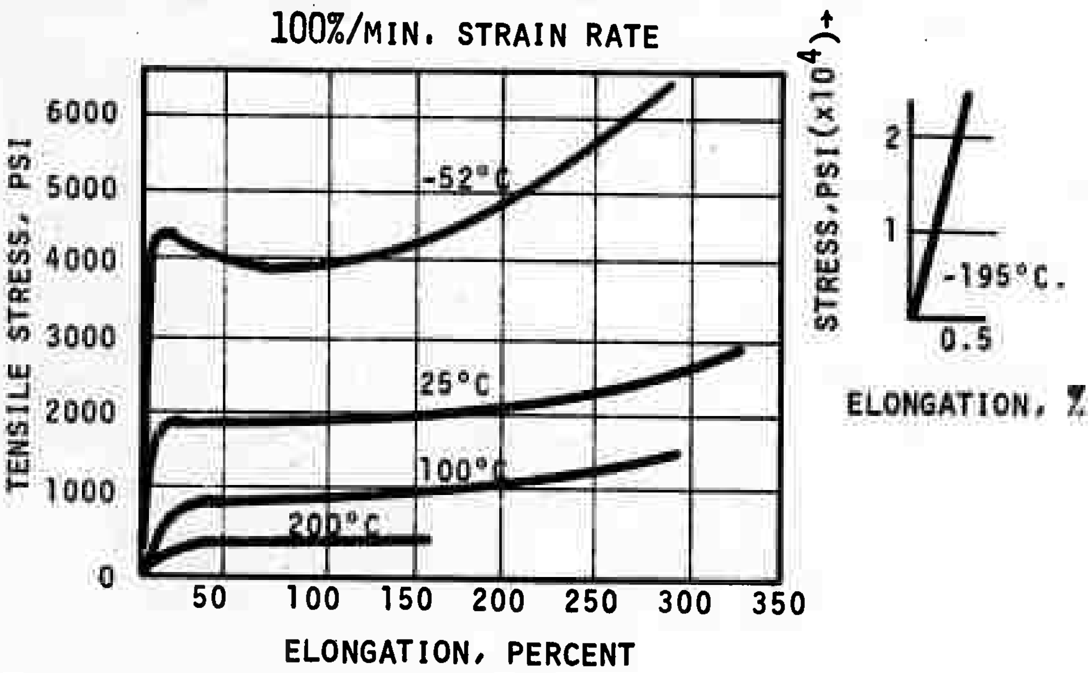
The tensile stress on the disk is readily evaluated from the thermal expansion coefficients for the ring, the Teflon and the disk when the tensile stress is known as a function of percent elongation. The tensile stress is given in Figure 3.5 as a function of percent elongation.

The percent elongation is easily calculated from

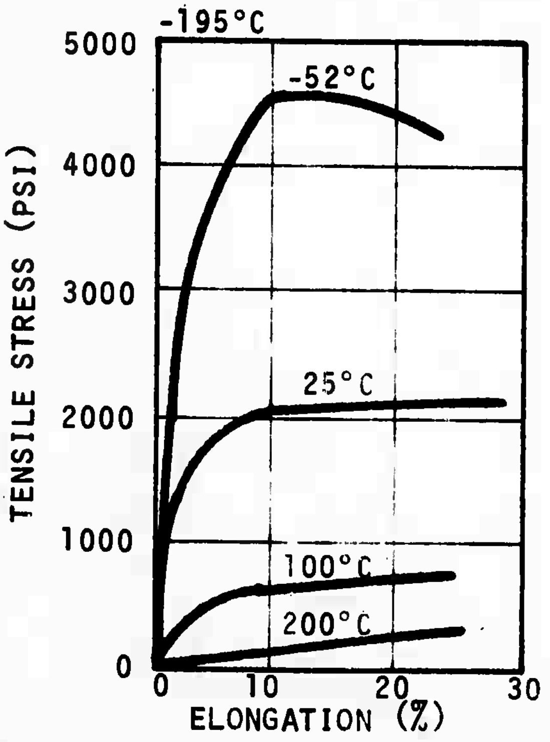
Figure 3.5

TENSILE PROPERTIES VS. ELONGATION *

100%/MIN. STRAIN RATE



TENSILE STRESS VS. ELONGATION



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* FROM REF. (1)

$$e = [R_R(300°C) - R_R(25°C)] - [R_d(300°C) - R_d(25°C)]$$

$$e = \frac{- [g(300°C) - g(25°C)]}{g} ,$$

Since

$$R_R(300°C) - R_R(25°C) = R_R \alpha_{TR} \Delta T = .00309\ R_R \text{ (window glass)}$$

$$R_d(300°C) - R_d(25°C) = R_d \alpha_{Td} \Delta T = .00267 R_d$$

$$g(300°C) - g(25°C) = 0.11g,$$

and

$$R_R = R_d + g \quad \text{(at 300°C)}$$

then

$$R_R^{25} = \frac{R_d^{25}(1 + \alpha_{Td}\Delta T) + 1.11g}{1 + \alpha_{TR}\Delta T} \quad \text{(at 25°C)} ,$$

Thus

$$e = \frac{R_R - R_d - g}{g}$$

$$e = \frac{\dfrac{R_d(1 + \alpha_{Td}\Delta T) + 1.11g}{(1 + \alpha_{TR}\Delta T)} - R_d - g}{g}$$

$$e = \frac{R_d(\alpha_{Td} - \alpha_{TR})\Delta T + g(.11 - \alpha_{TR}\Delta T)}{(1 + \alpha_{TR}\Delta T)g}$$

Since $\alpha_{TR}\ \Delta T << 1$ and letting $g = 0.01$cm, $\Delta T = 300°C$, $R_d = 1/2$cm and $\alpha_{Td} = 0.3 \times 10^{-6}/°C$, then

$$e \simeq (2643 - 150\ \alpha_{TR}) \times 10^{-4}$$

allows the tensile stress to be estimated. Both e and the tensile stress are plotted in Figure 3.6.

TENSILE STRESS AND ELONGATION AS A FUNCTION OF THE THERMAL EXPANSION COEFFICIENT OF THE HOLDING RING

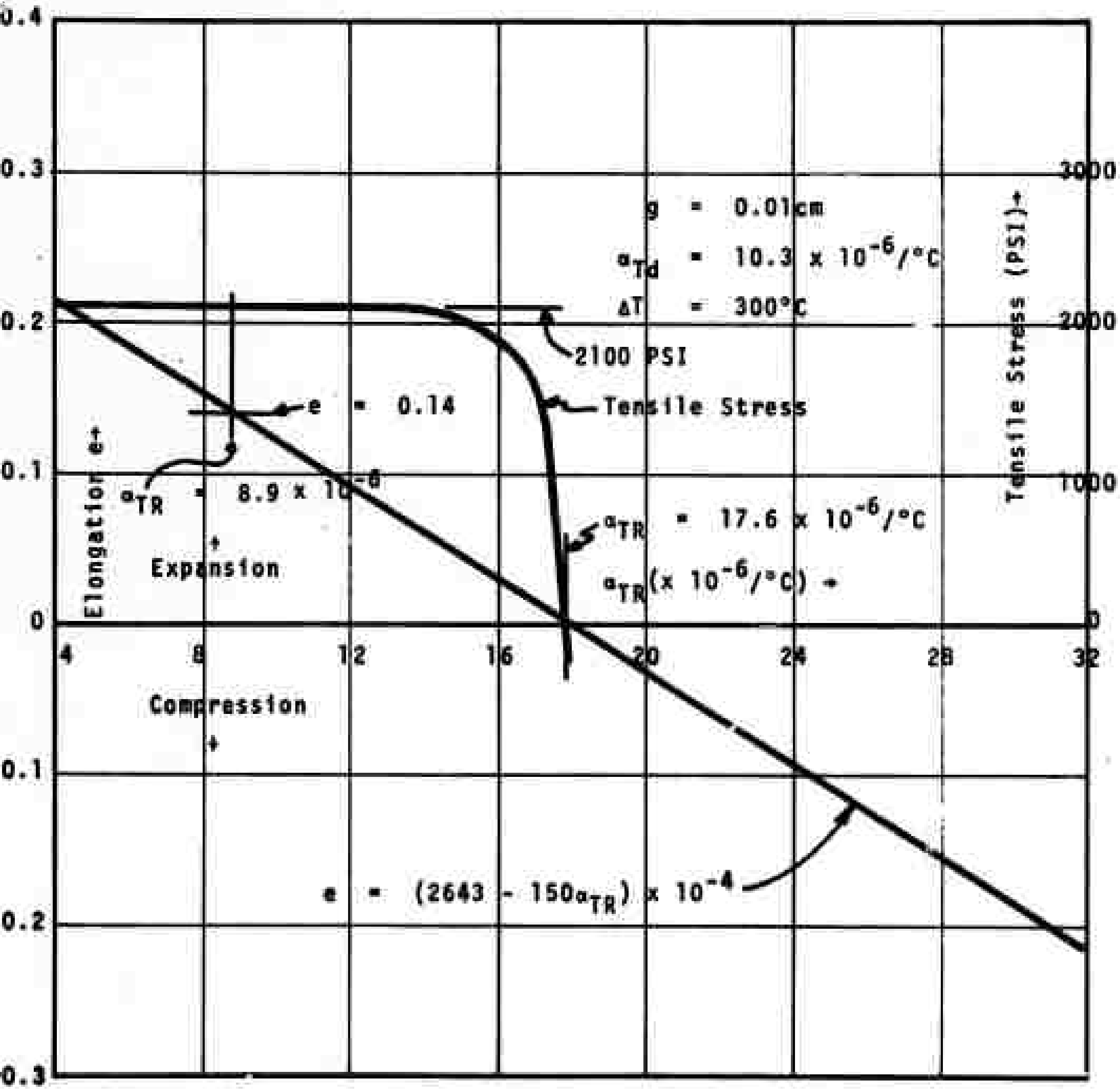


Figure 3.6

For window glass

$$\alpha_{TR} = 8.9 \times 10^{-6}/°C$$

and so

$$e = 0.14.$$

The tensile stress for this case is 2100 PSI.

The tensile stress can be made equal to zero by choosing α_{TR} and g so that

$$e = 0.$$

The relationship between α_{TR} and g is (see Figure 3.7)

$$\alpha_{TR} = \alpha_{Td} + \frac{g}{R_d} \left(\frac{.11}{\Delta T}\right) - \alpha_{TR}$$

$$\alpha_{TR} \approx 16 + 734g$$

for $\Delta T = 300°C$ and $\alpha_{Td} = 16/°C \; (\times 10^{-6})$, (see Appendix A).

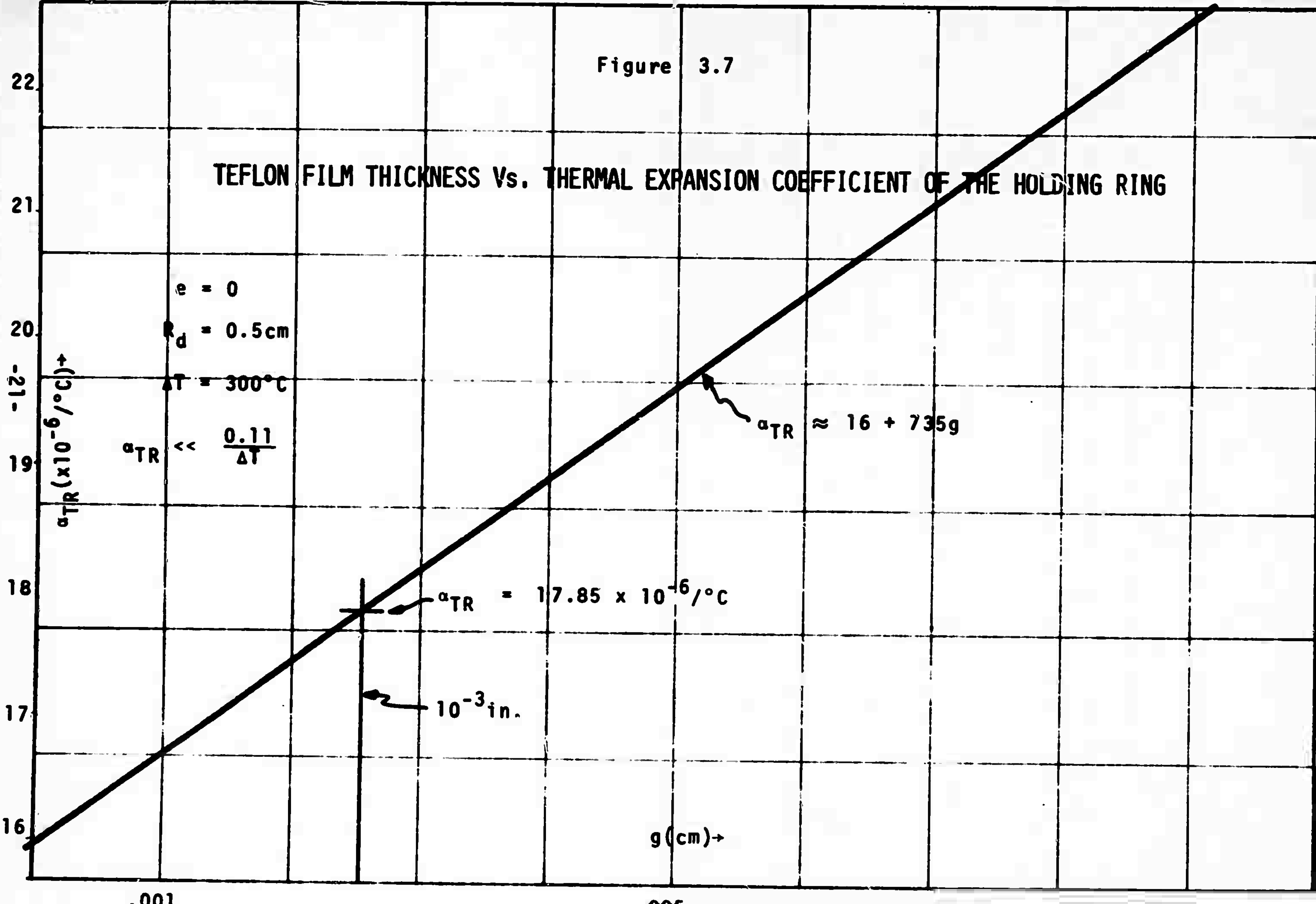


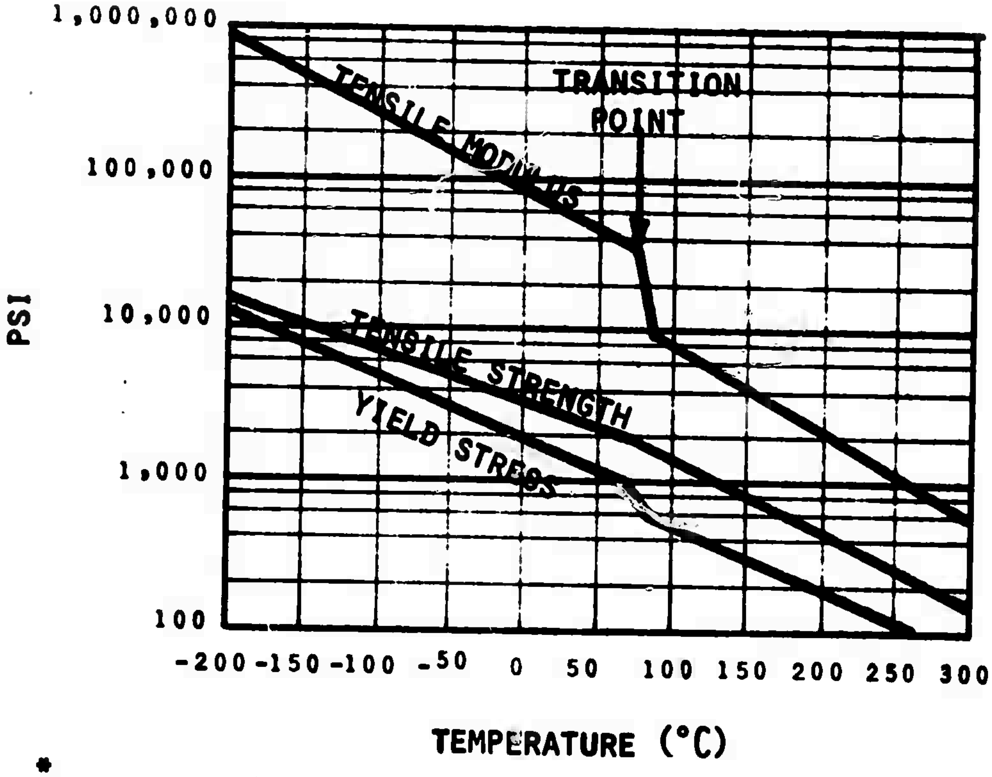
Figure 3.7

TEFLON FILM THICKNESS Vs. THERMAL EXPANSION COEFFICIENT OF THE HOLDING RING

The film thickness $g = 0.01\text{cm}$ used in Figure 3.6 is a typical value for an initial thickness (before melting) of about 10 mil (.025cm). The tensile stress indicated in Figure 3.6 does, however, seem unreasonably large for a disk/ring assembly. Glass/glass assemblies have been successfully bonded. The elongation in this case is $e \approx 0.11$ corresponding to a tensile stress of 2100 psi. The bond did not release when the assembly was cooled to room temperature. Whereas the yield point of the teflon/glass bond is unknown, it is doubtful whether it is anything like 2100 psi. The yield point at elevated temperatures has a much lower value (see Figure 3.8). Most likely the amount of elongation per unit temperature drop is small enough to maintain a yield point low enough to prevent separation of the teflon/glass bond.

The pump bands of Ho:YLF require that the ring be transparent out to about 1.6μ. It is more important to satisfy this requirement rather than to match thermal expansion coefficients, especially, since Teflon is quite easily deformed under pressure, even at room temperature.

TENSILE PROPERTIES Vs. TEMPERATURE*



* FROM REF. (1)

Figure 3.8

4.0 FABRICATION TECHNIQUE

There really should be no special problem involved in making a matched disk/ring set. They could be lapped together (see Figure 4.1) (like the glass stoppers in BOD bottles) to match the cone angles. If the disk is then polished off to the correct thickness we will then have the desired matched pai

4.1 WEIGHT REQUIRED TO PRODUCE A BONDING PRESSURE P

If the required bonding pressure is P (lb./in^2), the smaller radii of the YLF disk and ring are r_{d2} and R_{r2} respectively, the film thickness after bonding is t', the disk thickness is h and the cone semi angle is θ, then the weight required (see Figure 3.4) to produce the bonding pressure is

$$F = (P \sin \theta) [A]$$

FABRICATION OF A MATCHED YLF/RING PAIR

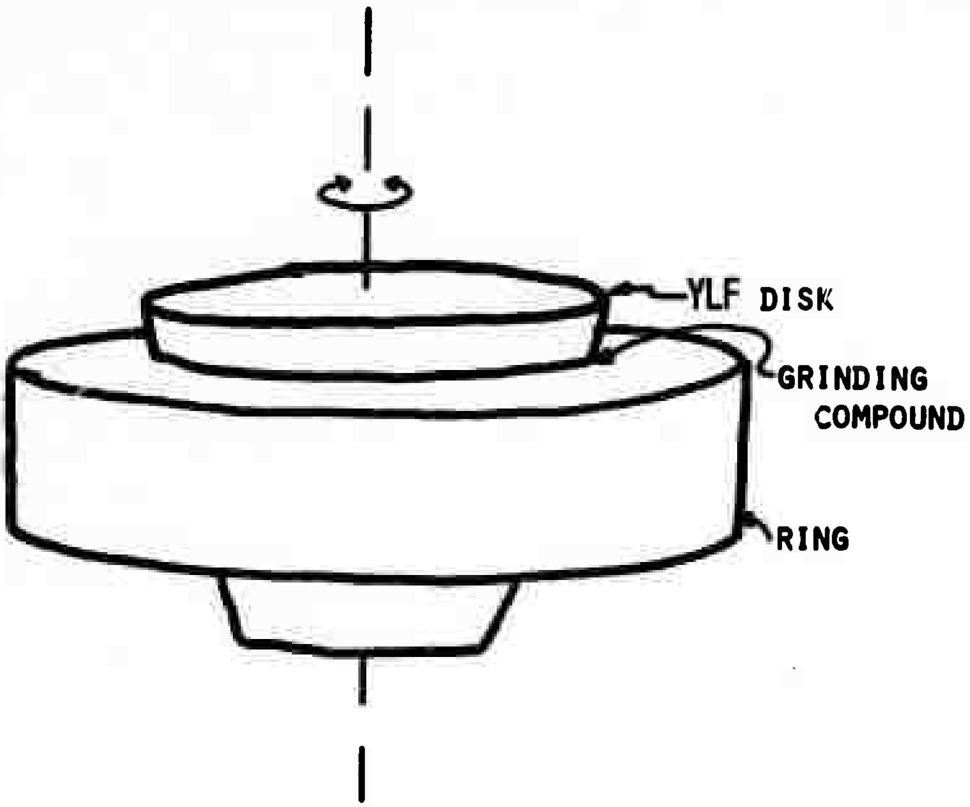


Figure 4.1

where A is the surface area of the disk:

$$A = \pi(r_{d1} + r_{d2}) \sqrt{h^2 + (r_{d1} - r_{d2})^2}$$

$$A \doteq \pi(2r_{d2}h \sec \theta)$$

Therefore,

$$F = \pi(2r_{d2})(h \sec \theta) P \sin \theta$$

Typical values are:

P = 200 lb./in.^{2}

h = 0.25cm

r_{d2} = 0.5cm

θ = 3°

$\sin \theta$ = 0.0523

Thus

$$F = 1.61 \text{ lbs.}$$

For a final film thickness $t' = 10$ mil.

$$R_{r2} = r_{d2} + t' \sec \theta$$

$$R_{r2} = 0.503\text{cm.}$$

4.2 PRELIMINARY EXPERIMENTS

An experiment has been conducted to evaluate this technique. The neck of a glass reagent bottle and its glass stopper were used in place of the glass ring and YLF disk, respectively. The dimensions of the stopper are given in Figure 4.2. The weight, several pieces of steel, totaled 4.39 lbs. A thermocouple placed at the top of the neck of the bottle indicated the temperatures.

The bonding pressure, P, for this experiment, where

$h = 0.788$ in.

$r_{d1} = 0.394$ in.

$r_{d2} = 0.315$ in.

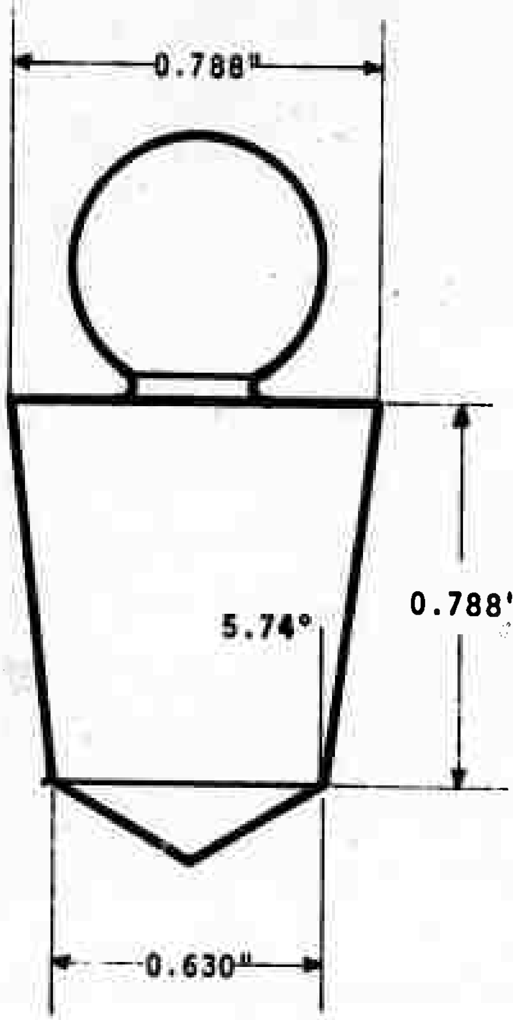
$F = 5.0$ lbs.

$\sin \theta = 0.1$

is

$P = 28.4$ lbs./in^2,

STOPPER DIMENSIONS



r_{d1} = 0.394 in.

r_{d2} = 0.315 in.

h = 0.788 in.

A = 1.75 in.^{2}

Figure 4.2

considerably lower than the one or two hundred PSI recommended by the manufacturer. Still a strong bond was achieved, most likely due to the rough glass surfaces.

4.3 QUALITY OF BOND

The above experiment securely bonded the stopper into the neck of the bottle. Other notable results are:

1) The seam where the Teflon film was butted together was not visible indicating that the film had melted and flowed together;

2) The Teflon was heated to too high a temperature. As a result it became very fluid and was pushed out both the bottom and the top of the stopper;

3) The film used was too thick as evidenced by the excess mentioned in 2). Probably a one or two mil thick film will suffice if the two surfaces have good contact everywhere;

4) A slight coloration of the stopper was noticeable where it had been bonded. It is not clear whether this coloration is natural (the Teflon does have a slight color) or whether it was induced by overheating.

4.4 STRENGTH OF BOND

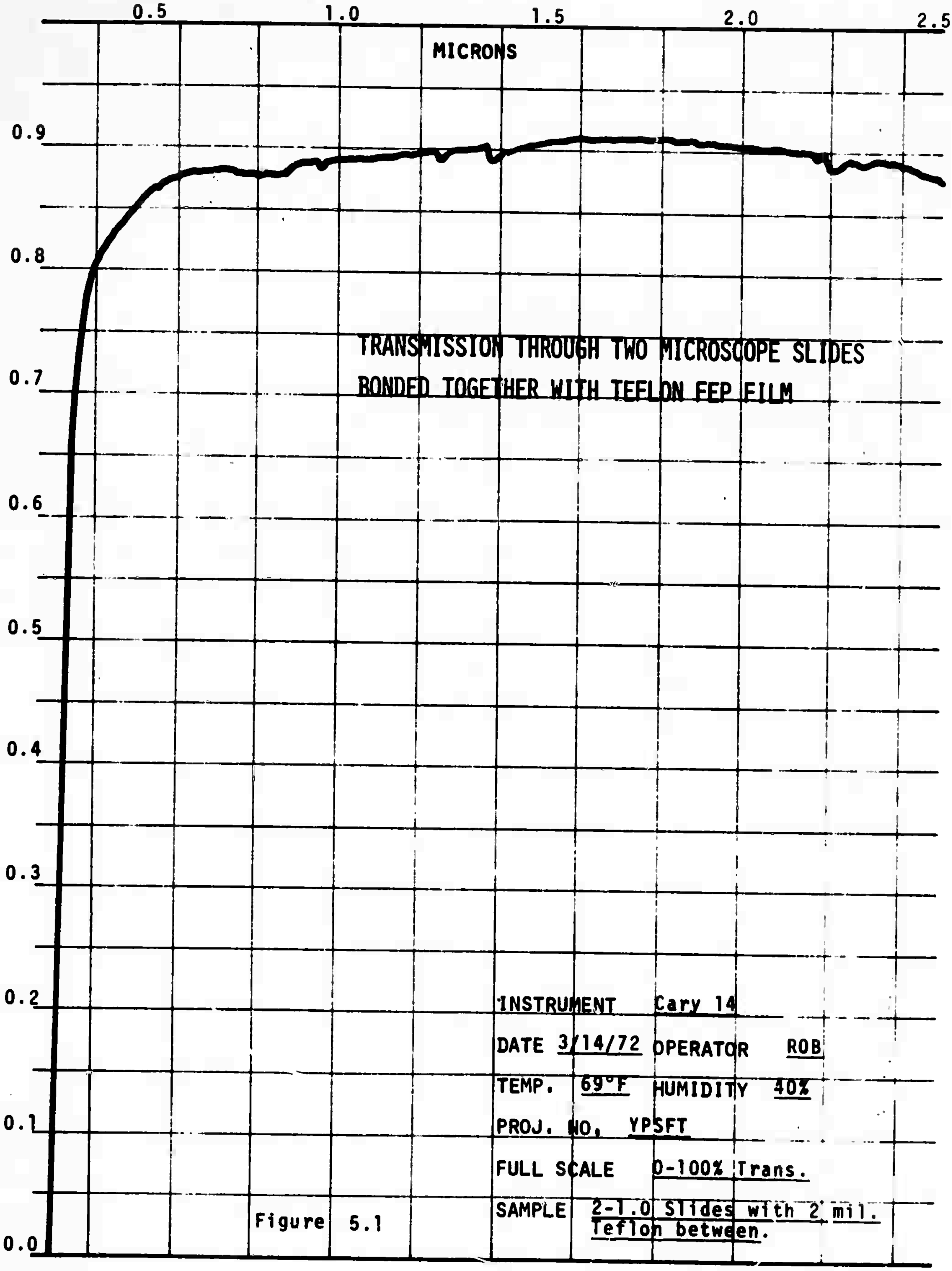
The bond could not be broken by pushing or pulling on the stopper by hand. No quantitative measurements have been made of the breaking point of the bond as it was felt that if it wouldn't release when manual pressure was exerted, the bond would be strong enough for the disk laser.

This was further tested by boiling it in water for 30 or 40 minutes while pulling it apart with a force of about two pounds. Again no sign of weakening occurred.

5.0 OPTICAL PROPERTIES OF TEFLON/GLASS BOND

The transmission of the Teflon bond was measured on the Cary 14 from 0.4μ to 2.5μ. The bond, in this case was formed by two microscope slides with the Teflon between them. The transmission curve is shown in Figure 5.1. For comparison, the transmission through two slides with an air gap was also measured (Figure 5.2). The bonded slides show a higher transmission than the two slides alone as would be expected since the Teflon has an index of refraction of about 1.36. Scattering causes a reduction in the indicated transmission in the visible region (see Figure 5.3). Such scattering is in no way detrimental to the pumping efficiency as, it should be remembered, most laser rods are fine ground on their surface anyway. The magnitude of the scattering is less in the IR as might be expected. The important thing to note is the lack of absorption.

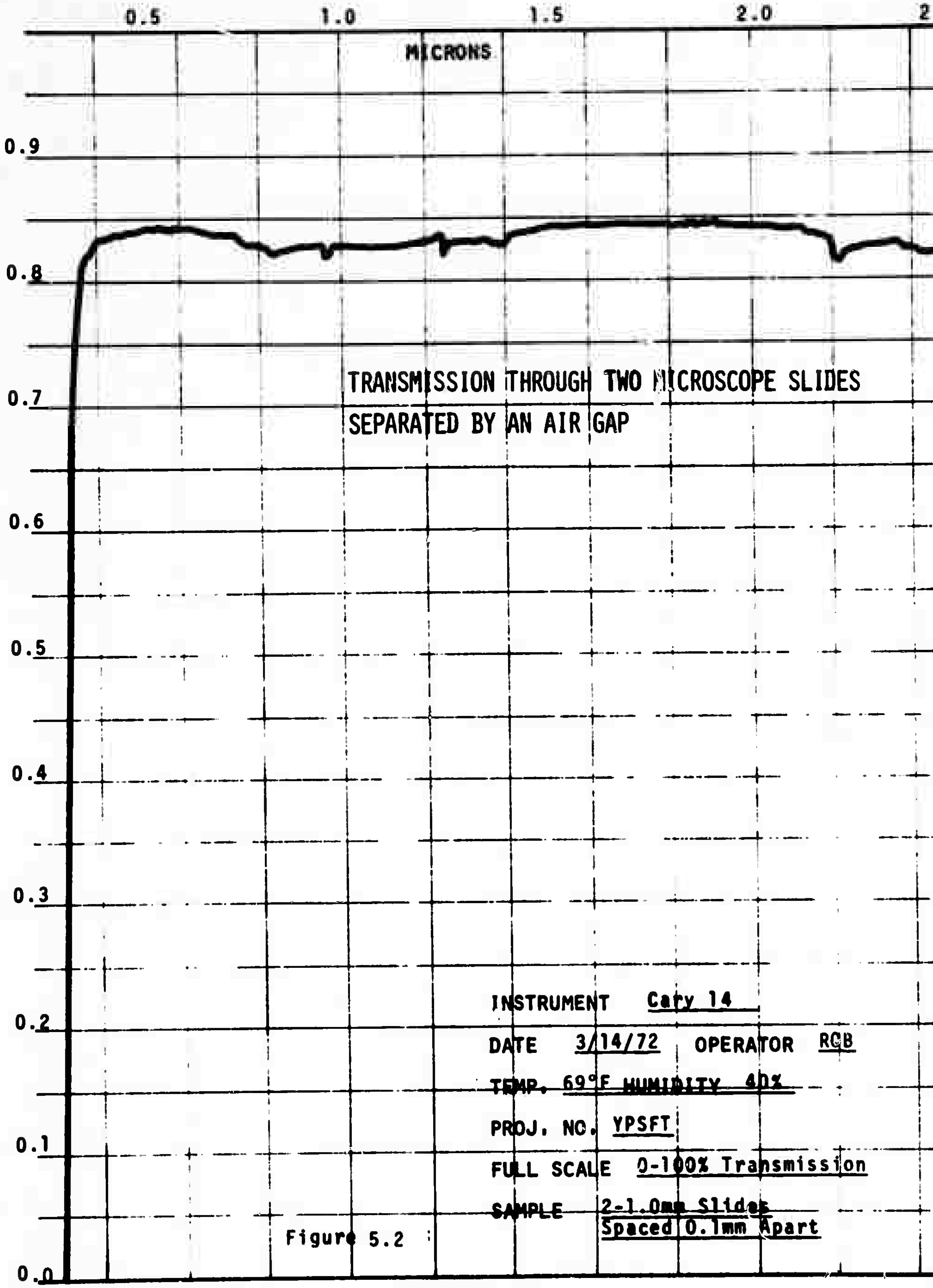
These transmission curves are in agreement with calculations of the transmission coefficients for the unbonded slides and bonded slides if one takes $n_{Teflon} = 1.36$ and $n_{slide} = 1.50$. Transmission curves of the Teflon film from 0.2μ to 15μ are given in Figures 5.4 and 5.5 (Ref. 1).



TRANSMISSION THROUGH TWO MICROSCOPE SLIDES BONDED TOGETHER WITH TEFLON FEP FILM

INSTRUMENT Cary 14
DATE 3/14/72 OPERATOR ROB
TEMP. 69°F HUMIDITY 40%
PROJ. NO. YPSFT
FULL SCALE 0-100% Trans.
SAMPLE 2-1.0 Slides with 2 mil. Teflon between.

Figure 5.1



TRANSMISSION THROUGH TWO MICROSCOPE SLIDES SEPARATED BY AN AIR GAP

INSTRUMENT Cary 14

DATE 3/14/72 OPERATOR RGB

TEMP. 69°F HUMIDITY 40%

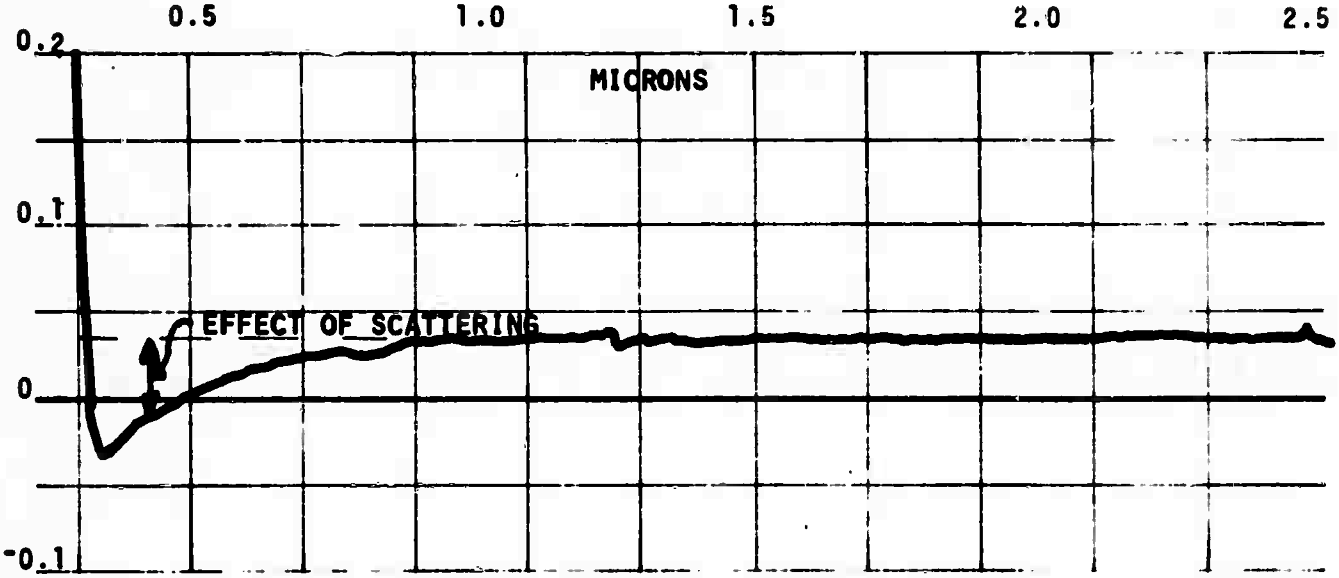
PROJ. NO. YPSFT

FULL SCALE 0-100% Transmission

SAMPLE 2-1.0mm Slides Spaced 0.1mm Apart

Figure 5.2

RATIO OF TRANSMISSION THROUGH BONDED SLIDES AND TWO SLIDES SEPARATED WITH AN AIR GAP

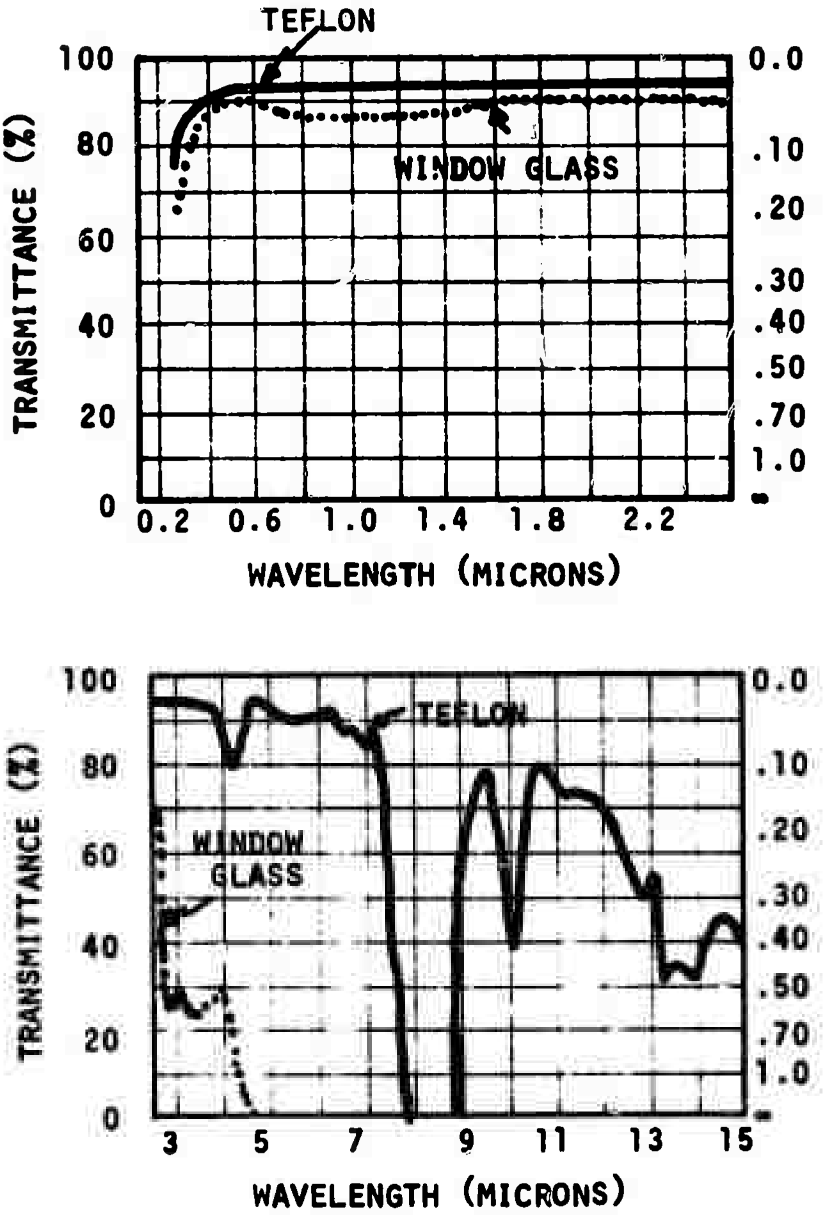


INSTRUMENT Cary 14
DATE 3/14/72 OPERATOR ROB
TEMP. 69°F HUMIDITY 40%
PROJ. NO. YPSFT CALIBRATION
FULL SCALE 50% - 150% Trans.
SAMPLE 2-1.0mm slides with 0.1mm spacer in ref. beam 2-1.0mm slides with 2 mil Teflon in sample beam.

Figure 5.3

Figure 5.4

ABSORPTION SPECTRUM FOR "TEFLON" FEP FILM *



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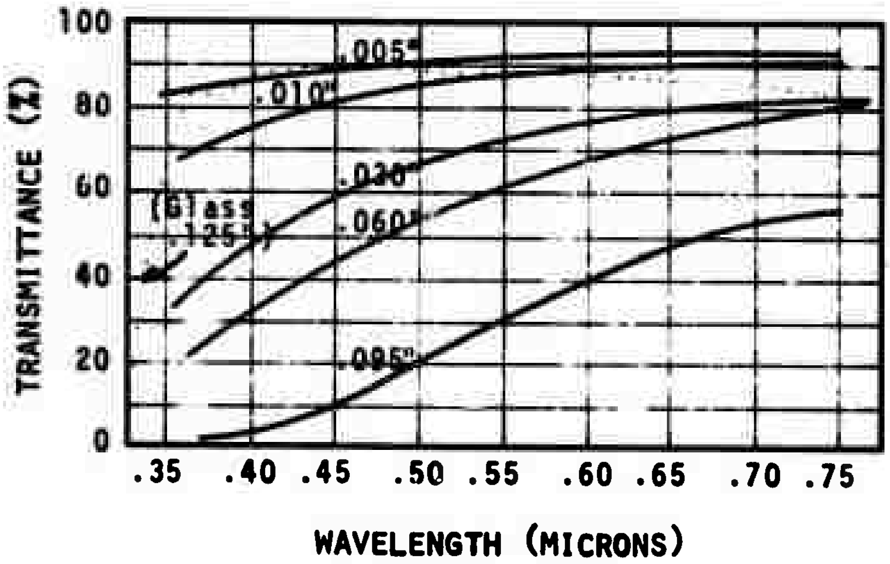
e refractive index of "Teflon"
P film is between 1.341 and 1.347.

rom Ref. (1).

LIGHT TRANSMISSION Vs. THICKNESS - "TEFLON" FEP FILM*



MEASURED ON A
CAREY MODEL 14
SPECTROPHOTOMETER

Figure 5.5

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* FROM REF. (1)

6.0 BONDING A Ho^{3+}:YLF DISK

Although bonding glass to glass may provide a useful technique for the fabrication of glass lasers, it in no way indicates whether or not a YLF disk can be bonded into a glass disk holder in this manner. A tapered disk and disk holder have been fabricated and successfully bonded together. The results of this first experiment with YLF are described briefly below.

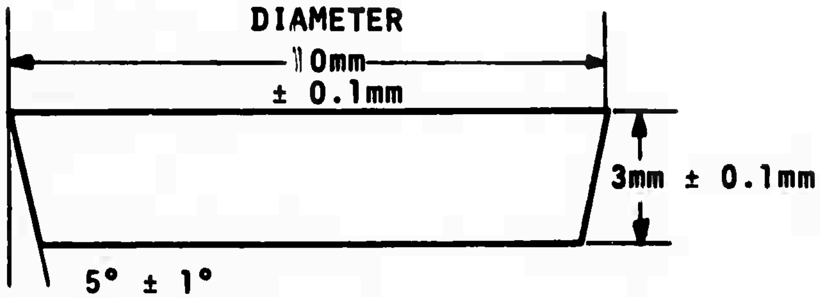
6.1 FABRICATION OF THE DISK AND DISK HOLDER

One disk and disk holder (see Figures 6.1 and 6.2) were fabricated by Valpey Corp., Mass. The tapered surfaces were left fine ground as it was felt that polishing would change the dimensions more than the tolerances allow. A photo of the finished pieces is given in Figure 6.3. Also shown in this photo are a rough boule slice and the Teflon FEP film used for bonding.

6.2 BONDING

Bonding the disk to the disk holder was performed easily and routinely. The disk, disk holder and 10 mil thick Teflon

L_iYF_4 DISK



THERMAL EXPANSION COEFFICIENT - $\alpha_T = 10.5 \times 10^{-6}/°C$

THERMAL CONDUCTIVITY - $R = 0.032$ watts/cm-°C

DENSITY - $\rho = 4.0$ gm/cm^3

SPECIFIC HEAT - $C = 0.8$ joules/gm-°C

INDEX OF REFRACTION - $n = 1.47$

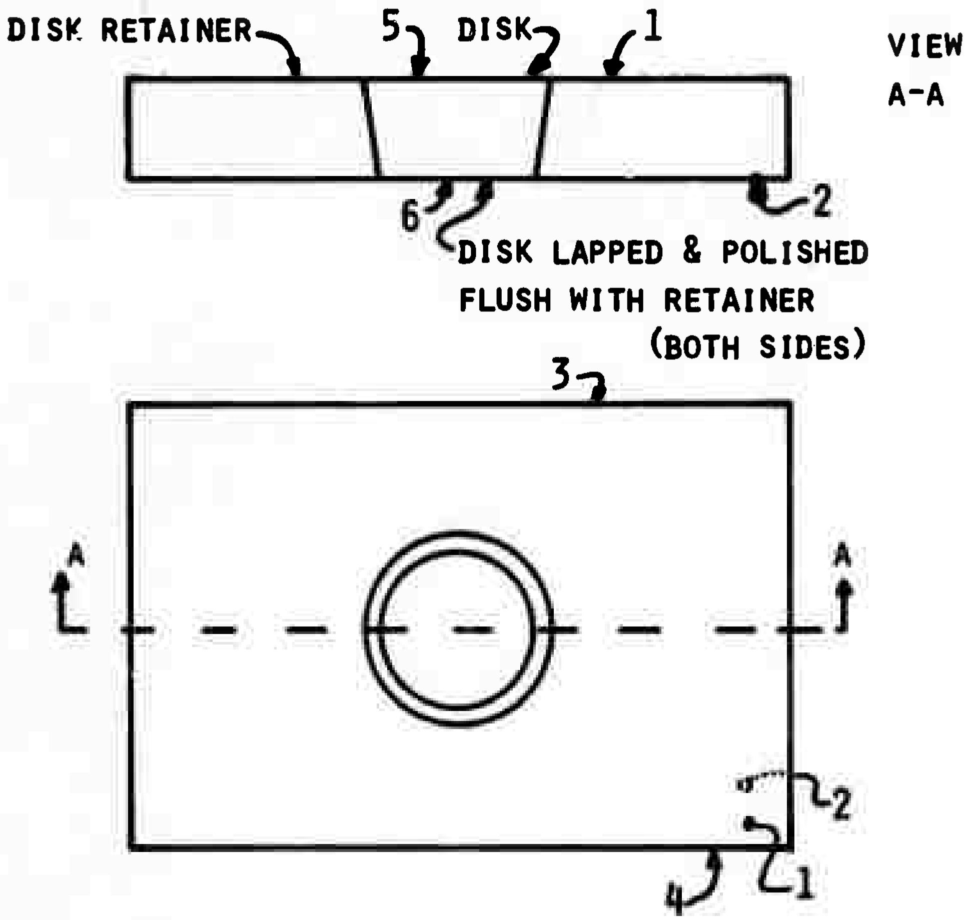
TENSILE STRENGTH - $\sigma_\theta = 15 \times 10^3$ PSI

YOUNG'S MODULUS - $E \approx 10^7$ PSI

HARDNESS - $\approx$ 5-1/2 MOH

Figure 6.1

DISK-RETAINER ASSEMBLY



Fabrication: $LiYF_4$ disk and plate glass retainer to be lapped together until the maximum gap at any point is less than 0.0005 in.

Polish: Surfaces 1, 2, 3, 4 must have commercial polish, no flatness tolerance. Surfaces 5 & 6 ($LiYF_4$ disk) must be flat to $\lambda/2$, parallel to 10 arc sec.

Figure 6.2

COMPONENTS FOR THE FIRST BONDED YLF DISK

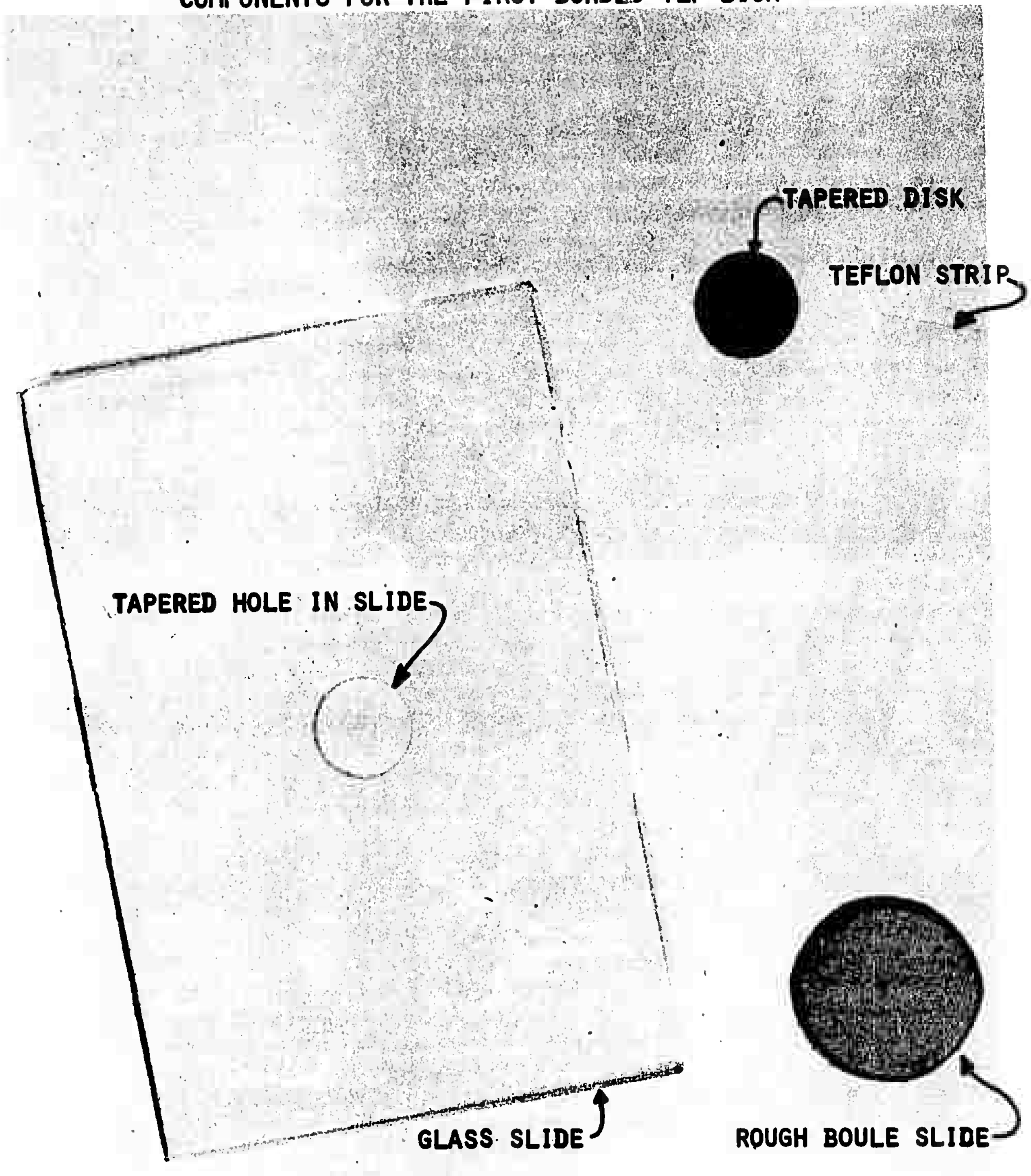


Figure 6.3

FEP film were throughly cleaned prior to assembly. A special jig was used to hold the disk holder and the weight which would allow the disk and weight to settle freely when the Teflon melted. The entire assembly was heated to about 650°F and allow to cool overnight.

6.3 RESULTS

The disk and holder were securely bonded (see Figure 6.4). No strains could be seen in the disk when it was viewed through crossed polarizers. The disk did not fracture.

BONDED DISK

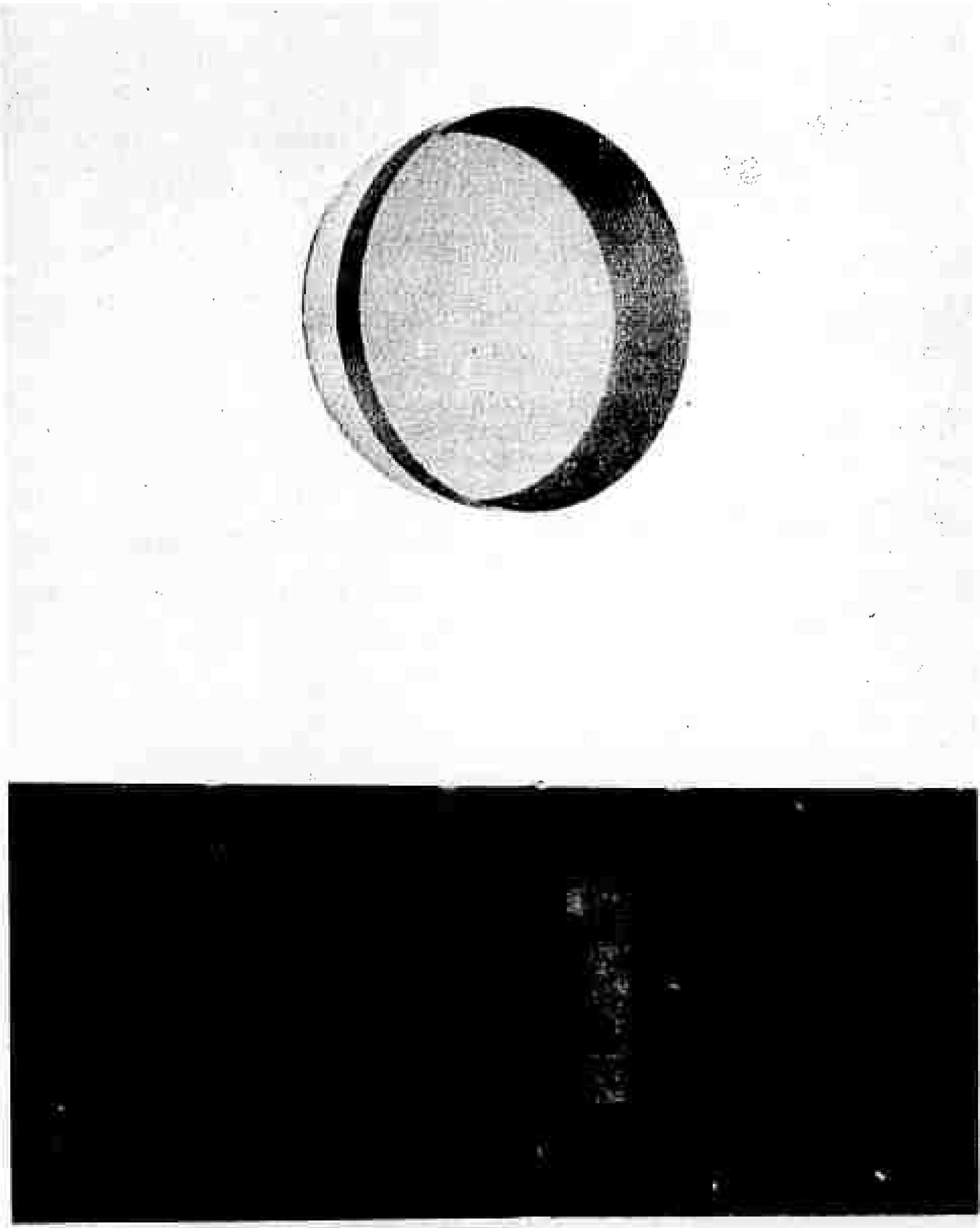


Figure 6.4

REFERENCES

1. Product Bulletin on DuPont Teflon Fluorocarbon Film, DuPont de Nemours & Co. Plastics Dept., Fluorocarbons Division, Wilmington, Del.

2. Private Communication, R. Folweiler.

3. Private Communication, A. Linz.

4. Private Communication, E. Chicklis.

5. E.P. Chicklis et al, Appl. Phy. Lett, 19, 119 (1971).

6. $\alpha_n \approx 6 \times 10^{-6}$ for CaF_2, T.W. Houston et al, J. Opt. Soc. Am., 53, 1286 (1963).

7. Measured by Dynatech Corp.

8. E.I. DuPont de Nemours & Co., Wilmington, Del., "FREON" E Series Product Information EL-8B.

APPENDIX A

MATERIAL PROPERTIES OF Ho:YLF

The material properties of Ho:YLF required for the calculations in 3.3 are given in Table I.

TABLE I

Ho:YLF MATERIAL PROPERTIES

$k = 3.2 \times 10^{-2}$ W/cm - °C (2)

$\nu \approx [.2]$ (3)

$\sigma_\theta \approx 15 \times 10^3$ PSI (2)

$\alpha_{Td} \approx 12.3 \times 10^{-6}/°C$ (15)

$E = 10^7$ PSI (2)

$\alpha = [.05/cm]$ (4)

$\sigma = 1.2 \times 10^{-19} cm^2$ (5)

$\tau_{sp} \approx 20 \times 10^{-3}$ sec (5)

$\tau_u \approx 12 \times 10^{-3}$ sec (5)

$h\nu = 9.65 \times 10^{-20}$ Joules

$\Delta\nu \approx 7 \times 10^{11} Hz$ (5)

$n \approx 1.47$ (3)

$\alpha_{nd} = [-10^{-5}/°C]$ (6)

$\frac{t_{sp}}{h\nu} = 7.07 \times 10^{17}$

$\frac{h\nu}{t_{sp}} = .483 \times 10^{-17}$

OTAL PERCENT ELONGATION Vs. MPERATURE FOR Ho:YLF (A-AXIS)*

TABLE II

T(°C)	$\frac{\Delta \ell}{\ell_o}$
-196°	0
-150	1.5×10^{-4}
-100	4.8
-50	9.5
0	15.3
50	21.8
100	29.1
150	37.8
200	47.1
250	57.0
300	67.5
350	78.0
400	88.5

THERMAL EXPANSION COEFFICIENT Vs. TEMPERATURE FOR Ho:YLF (A-AXIS)*

TABLE III

T(°C)	α_T(°C^{-1})
-174	3.41×10^{-6}
-125	6.60
-75	9.40
-25	11.60
25	13.00
75	14.6
125	17.4
175	18.6
225	19.8
275	21.0
325	21.0
375	21.0

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* REF. (15)

Figure A.1

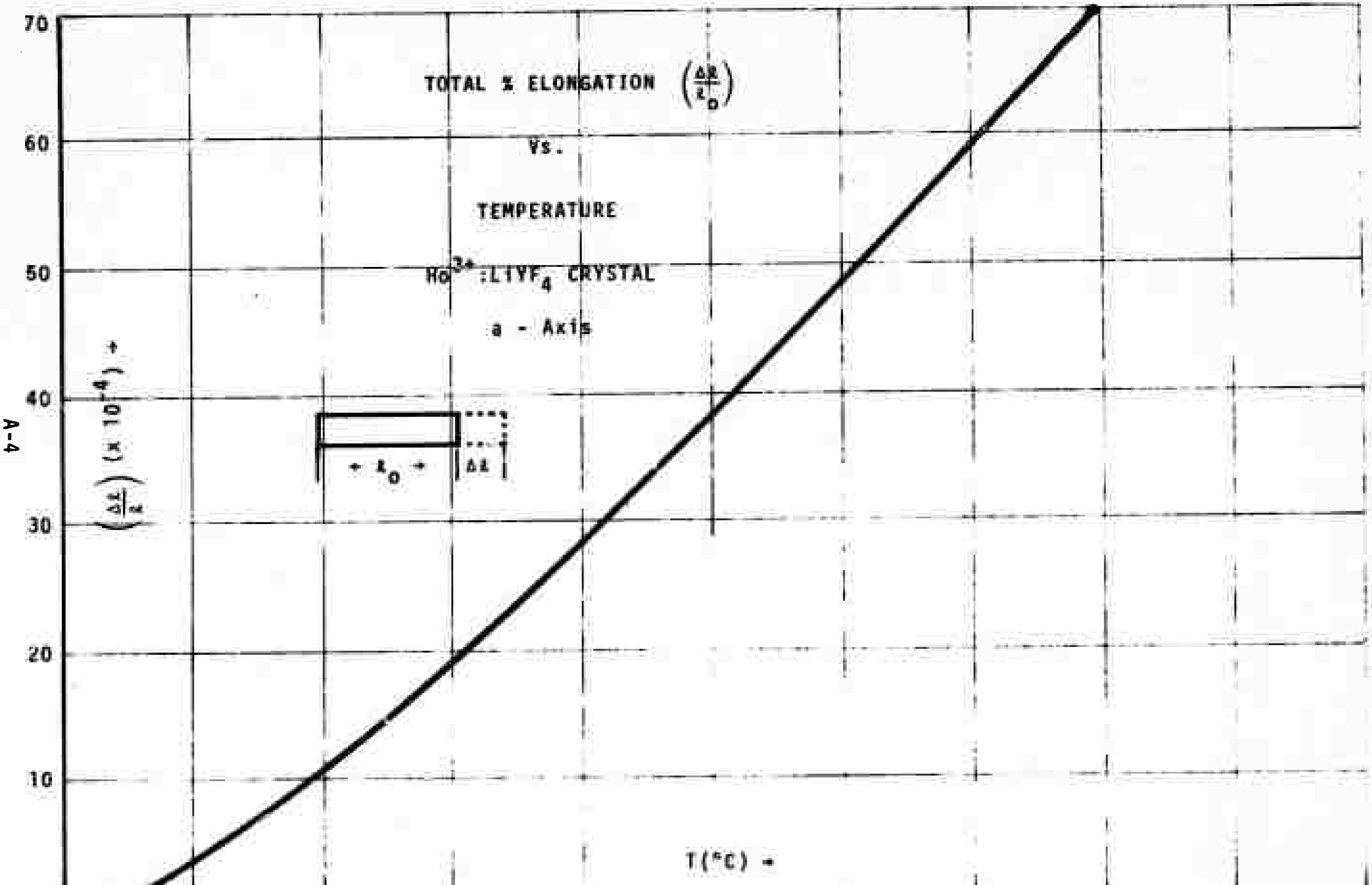
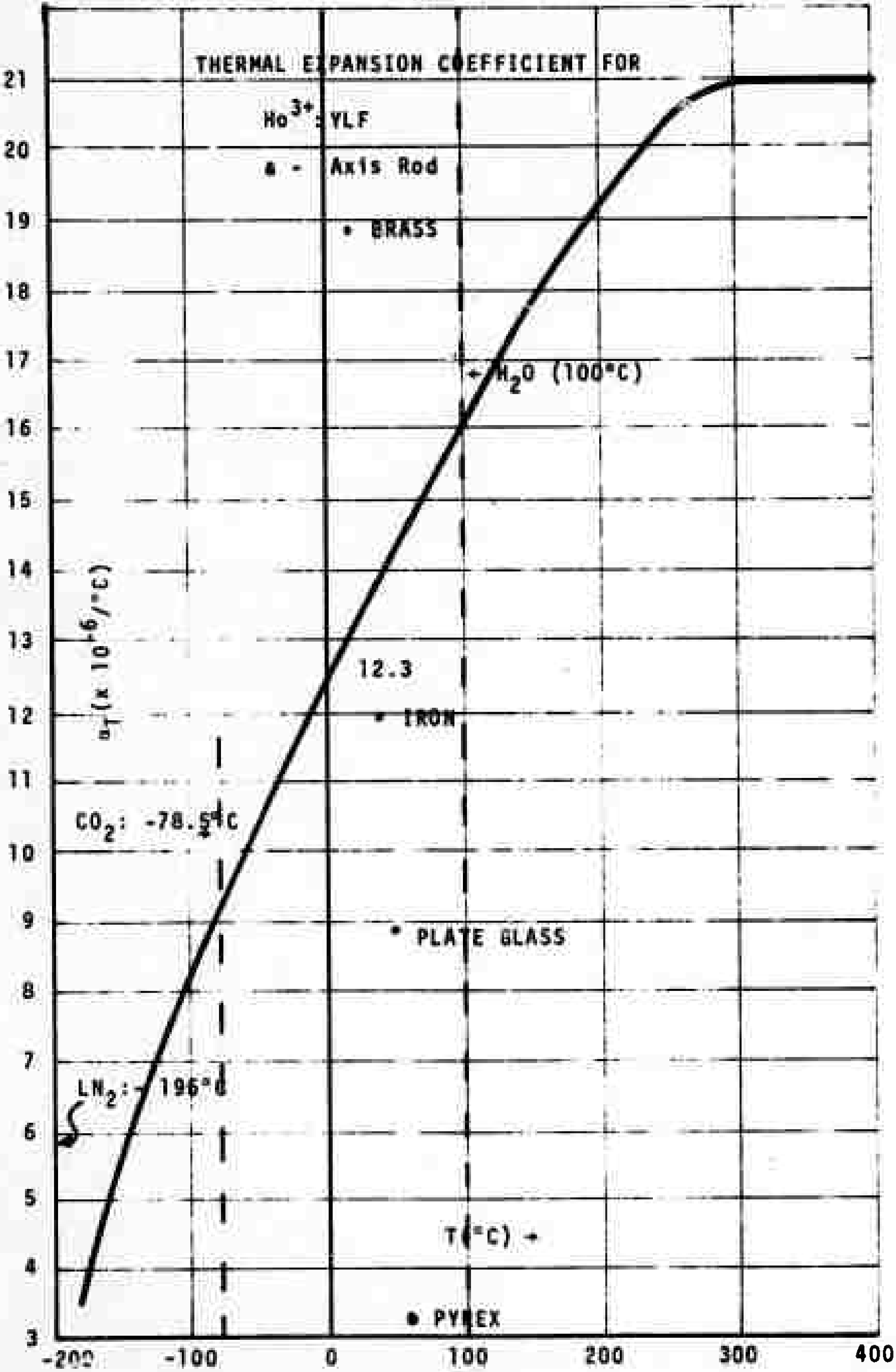

TOTAL % ELONGATION $\left(\frac{\Delta\ell}{\ell_0}\right)$
Vs.
TEMPERATURE
Ho^{3+}:LiYF$_4$ CRYSTAL
a - Axis
← ℓ_0 →
$\Delta\ell$
$\left(\frac{\Delta\ell}{\ell}\right)$ (x 10^{-4}) →
70
60
50
40
30
20
10
T(°C) →

Figure A.2


• ALUMINUM
THERMAL EXPANSION COEFFICIENT FOR
Ho^{3+}:YLF
a - Axis Rod
• BRASS
← H_2O (100°C)
12.3
• IRON
CO_2: -78.5°C
• PLATE GLASS
LN_2: -196°C
T(°C) →
• PYREX
α_T (x 10^{-6}/°C)
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
-200
-100
0
100
200
300
400

APPENDIX B

PROPERTIES OF THE FREON COOLANT

TABLE IV

FREON E-3 properties (8)

α_{nc} = $-.497 \times 10^{-3}/°C$ (11)

C_c = $1.01\ J/gm{-}°C$ (12)

ρ_c = $1.75\ gm/cm^3$