

NASA CR 156674

(NASA-CR-156674) DEVELOPMENT OF
BIREFRINGENT FILTERS FOR SPACEFLIGHT
(Lockheed Missiles and Space Co.) 48 p HC
A03/MF A01 CSCL 20F

N78-19927

Unclas
63/74 07301

DEVELOPMENT OF BIREFRINGENT FILTERS FOR SPACEFLIGHT

NAS Contract No. NAS 5-22368

JULY 1976

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This study was performed under the auspices at the Solar Physics Quick Reaction
and Special Purposes Facility Definition Team (Contract NAS 5-22368) for the Shuttle/Spacelab
Payloads Project, Goddard Space Flight Center, NASA.

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GENERAL INTRODUCTION

This report is on work done for the NASA Solar Physics Spacelab Quick Reaction and Special Purpose Facility Definition Team on the critical problems of a space qualified birefringent filter suitable for use on an H α /magnetograph. This report uses data, fabrication techniques and computer programs for the analysis of birefringent systems previously developed by the Lockheed Solar Observatory. The construction design philosophy of the filter modules tested as well as the construction techniques were based on previous experience with numerous birefringent filters.

The critical problem for flight of a birefringent filter is the shock mounting of the calcite. The design presented here bonds the calcite block with silicon rubbers to the calcite holder. The calcite together with its all necessary polarizers and rotating achromatic plates are mounted together in units called a filter module. By using a set of modules containing calcite crystals of differing lengths, a filter can be produced. A description of the modules is contained in Section I. Also described in Section I is a container for the filter modules, which can be used both to hermetically seal the system or contain an index matching oil.

A second serious problem with birefringent filters has been wavelength drifts introduced by thermal variations. The traditional approach to the thermal drift problem has been a hardwired temperature controller and oven enclosure for the calcite. Section II reports on the response of a filter element while being controlled by the Lockheed Temperature Control.

A tunable filter such as proposed for the H α /magnetograph offers the possibility of using the tuning elements to compensate for any thermal drifts thus eliminating any need for a hardware temperature controller if the rate of change of wavelength with temperature is known. Section III describes the determination of the wavelength sensitivity to temperature of calcite. The

Lockheed Universal filter has been built with temperature sensors on the calcite elements. Section IV describes operation of the filter using a software control algorithm instead of a hardware temperature controller.

Section V briefly reviews some radiation considerations of filter systems. Also included is an appendix that indicates future areas of research for filter materials and systems.

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I. SPACE HARDENED FILTER MODULES

INTRODUCTION

The goal of the space hardening experiments was to contain calcite elements in a cell that would sustain both shock testing and thermal cycling. It was desired that the cell also contain the necessary components for a complete tunable module. A preliminary test model was used to verify the cell design, a prototype was designed to verify the tunable module, and an oil sealed prototype to verify a complete filter assembly.

In addition, optical cementing techniques were developed to allow reliable cement bonds between calcite to calcite, calcite to glass, and calcite to polyvinyl alcohol (PVA). Bonding was of some concern because previous calcite cements had a tendency to cause fracture when bonded assemblies were thermally cycled. Reliable cements allow construction of filters that do not require index matching oils.

SHAKE TEST

Preliminary Test Unit

Before making a full 30 mm aperture 1Å filter module, a test unit with 25 mm aperture was constructed. The test unit consisted of 4Å and 2Å wide field elements. Table I lists the components of the Mark I test unit. The test unit was constructed with and sealed in its housing with GE RTV 602. The test units were shaken to the specification given in Astronomy Spacelab Payload Accommodations and Interfaces Handbook (May 1975), Figure 4.2.2.2-1 (reproduced in Figure 1). The unit was shaken in three orthogonal axis, where the y axis was parallel to the filter optical axis. A sample shake test chart is shown in Figure 2.

The first test unit shake, 2-25-76, showed separation of the waveplates and their cover glasses. The separation was evident from fringe patterns

seen when the filter was mounted over a diffuse helium source. A photograph of the fringes is shown in Figure 3. The filter was disassembled and the separation of the waveplates was verified. The failure was attributed to the poor bond between RTV 602 and the polyvinyl waveplate material.

Although the separation occurred, the calcite showed no evidence of damage nor did any of the components rotate with respect to each other. The spectral performance of the Mark I version of the test unit did not change.

The test unit was rebuilt using Eastman Kodak HEF-4 optical cement to bond the waveplate material. The glass covers of the polyvinyl in intermediate positions in the filter were eliminated. The optical component list is shown in Table II. The filter was bonded in the cell with RTV 602 as before. The mechanical drawing of the Mark II system is shown in Figure 4. A photograph of the cell and shake fixture are shown in Figure 5.

Kodak HEF-4 is a non-hardening optical cement. Calcite elements have been cemented with HEF-4 and temperature cycled between 20° and 60°C.

On 3-17-76 the unit was reshaken. No separation was observed. No evidence of any adverse effects was shown by the filter. Spectral performance was not affected.

Prototype Filter Module

After the successful experience with the test unit a flight prototype unit was constructed. The flight prototype unit has an achromatic half waveplate and a rotating polarizer. Its optical components are listed in Table III. A mechanical diagram and a photograph are shown in Figures 6 and 7.

On 5-4-75 the prototype unit was successfully shaken. The calcite did not rotate and the spectral performance was unchanged.

The calcite used was fabricated by Halle Nacht and has two small cracks on its edge. This calcite was especially chosen to see if the cracks would increase. They did not.

TABLE I
MARK I COMPONENTS LIST

<u>Material</u>	<u>Thickness (cm)</u>	<u>Orientation</u>	<u>Comment</u>
1. Glass	.203		Bonded to 2- RTV 602
2. $1/4 \lambda$ (PVA)	.00254	45°	3
3. Glass	.203		4
4. Calcite	.254	0°	5
5. Glass	.203		6
6. $1/2 \lambda$ (PVA)	.00254	45°	7
7. Glass	.203		8
8. Calcite	.254	90°	9
9. Glass	.203		10
10. HN-38 (PVA)	.00254	0°	11
11. Glass	.203		12
12. Calcite	.127	90°	13
13. Glass	.203		14
14. $\lambda/2$ (PVA)	.00254	45°	15
15. Glass	.203		16
16. Calcite	.127	0°	17
17. Glass	.203		18
18. $\lambda/4$ (PVA)	.00254	45°	19
19. Glass	.203		

TABLE II

MARK II COMPONENTS LIST

<u>Material</u>	<u>Thickness (cm)</u>	<u>Orientation</u>	<u>Comment</u>
1. Glass	.203		Bonded to 2 - HEP4
2. $1/4 \lambda$ (PVA)	.00254	45°	3
3. Calcite	.254	0°	4
4. $1/2 \lambda$ (PVA)	.00254	45°	5
5. Calcite	.254	90°	6
6. HN-38 (PVA)	.254	0°	7
7. Calcite	.127	90°	8
8. $\lambda/2$ (PVA)	.00254	45°	9
9. Calcite	.127	0°	10
10. $\lambda/4$ (PVA)	.00254	45°	11
11. Glass	.203		

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TABLE III
 Prototype Components List

<u>Material</u>	<u>Thickness (cm)</u>	<u>Orientation</u>	<u>Comment</u>
1. Glass	.203	Rotates	Bonded to 2 with HEF-4
2. HN-38	.00254	as	3
3. Glass	.203	unit	
4. Space	.114		
5. Glass	.203		Bonded to 7 with HEF-4
6. $\lambda/4$ (PVA)	.00254	45°	8
7. Calcite	.5588	0°	9
8. $\lambda/2$ (PVA)	.00254	15°	10
9. $\lambda/2$ (PVA)	.00254	75°	11
10. $\lambda/2$ (PVA)	.00254	15°	12
11. Calcite	.5588	90°	13
12. HN-38	.00254	0°	14
13. Glass	.203		

SEALED FILTER ENCLOSURE

After the successful shake test of the prototype filter module the spur gears were replaced by bevel gears which were more suitable for the rotary feed-through system used for the sealed enclosure assembly. The enclosure was designed as a hermetic or oil sealed case for the birefringent filter. The enclosure actually built is just sufficiently long to contain the prototype filter module, but a larger enclosure with more feed-throughs could contain any number of filter modules.

The enclosure was built with O-ring seals at all the non-rotating joints. The enclosure components and the complete enclosure are shown in Figs. 8 and 9. For a flight unit epoxy or welded seals might be judged more suitable. The rotary feed-through necessary to control the tuning module has no rotary oil seal. Rather, rotary motion is transferred through an intermediate plate that rocks. The plate is welded to a metal bellows which in turn is welded to the side of the feed-through so that there is no piercing connection between the input and output shafts. No magnets of any kind were used in the seal.

The enclosure was tested for gas tightness by flooding the exterior with helium while pumping on the interior with a vacuum pump. A helium leak detector in the output part of the pump showed no leakage signal. The tuning motor was operated as the unit was pumped. Following the gas seal tests the enclosure was filled with index matching oil and placed in a vacuum chamber. After forty hours in the chamber at 10^{-6} torr no oil was detectable on the surfaces of the container. The motor was operated periodically while the unit was in the vacuum chamber.

On 6-25-76 the oil filled enclosure was shaken to the shuttle shake profile. At the time of the shake test the enclosure contained the prototype filter module. No oil leakage was observed after the shake. The unit was then replaced in the vacuum chamber and left in vacuum for 16 hours. The motor was periodically rotated. After removal from the vacuum chamber, no leakage was observed.

The oil inspection was carried out by wiping a clean cotton swab over all metal parts. The exposed optical surfaces were visually inspected. Any oil filter would create interference colors or tint, none were observed.

A-R COATING POSSIBILITIES

A major problem with ground based filters has been leaking and contamination of the index matching fluid or oil in the filter. In space, the consequences of leakage are much more severe. One solution to the leakage problem is to completely seal the filter as described above. Another is to eliminate the index matching fluid.

The index matching fluid serves two purposes. The first is to eliminate fresnel reflection losses at the interfaces. The second is to eliminate image displacement caused by rotating tilted optical elements in the filter. During this study a cementing technique has been developed which allows reliable stress-free assembly of calcite to calcite and calcite to glass. The index of the cement is 1.57. The index of the cement used for the waveplate is 1.54.

If a Lyot filter is constructed from a set of turnable modules of the form half wave, quarter wave, calcite, half wave, calcite, polarizer where the first half wave plate rotates and all the other components are cemented together, there are only four air-glass interfaces per module. A plot of maximum transmission, neglecting polarizer losses, versus number of modules is shown in Fig. 10 for several values of per surface reflection loss. Shown in Fig. 11 is the per surface reflection loss for a sample four layer antireflection coating. From 4300Å to 6600Å the per surface reflection loss is less than 0.2%. This spectral region spans the useful region of currently available polarizing materials. Recent developments suggest coatings may be available that have reflectance less than 0.2% over the entire range from .3 to 2.2 microns.

For the filter design suggested above, only the half wave plates rotate. If the half wave plates are 0.25 cm thick and are mounted in 5-cm ring bearings with less than 1.25×10^{-3} cm axial play, then the displacement of the optical beam through the plate is

$$d = t\theta \left(\frac{n-1}{n}\right)$$

$$d = (2.5 \times 10^{-1}) \left(\frac{1.25 \times 10^{-3}}{2.5}\right) \left(\frac{.52}{1.52}\right)$$

$$d = 4.14 \times 10^{-5} \text{ cm}$$

An image scale of 40 arc seconds per cm is such that 0.1 arc second occupies 2.5×10^{-3} cm, the size of a typical diode array element. A 40 π cm scale thus is nearly 2 orders of magnitude greater than any image motion caused by rotation.

To verify that a cemented filter would operate well, one of the observatory Halle H α filters was disassembled, degreased, and reassembled with cemented components and A-R windows. The filter is now in routine use in the observatory patrol system.

The rebuilt Halle has been repeatedly cycled between 10°C and 50°C. At present it is left outside with the power off during the evening hours and is also uncovered during normal operation in order to subject the cement bonds to larger than normal thermal loads.

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TEMPERATURE CONTROLLER TESTS

PURPOSE

The purpose of the thermal controller tests was to evaluate the ability of a stand alone temperature controller to maintain the temperature of calcite filter elements in the presence of environmental thermal loads and solar heating. The temperature controller used was the Lockheed Filter Controller designed by R. Lindgren. This device senses ambient temperature and supplies a steady state heat input based on the difference between ambient and the control temperature. In addition, it applies a fine control heat input based on a sensor near the calcite crystal. The power input follows the law:

$$HI = k_1(t_c - t_a) + k_2(t_c - t_s)^2 \operatorname{sgn}(t_c - t_s) + k_3$$

where k_1 , k_2 and k_3 are adjustable parameters, and t_c , t_s and t_a are respective the control, sense, and ambient temperature values. If the sensed temperature is greater than the desired control temperature, the ambient control heat input is reduced. The control input is limited to be less than 20 percent of the ambient heat input.

METHOD OF MEASUREMENT

Two fundamentally different systems were used to measure the characteristics of the controller. One, using a quartz crystal thermometer, measured the temperature in the oven close to the calcite. The second measured the mean temperature through the crystal using a laser probe. The laser probe allowed measurements of possible temperature inhomogenities in the calcite itself. Measurements were made on a $.08\text{\AA}$ wide field filter element which was installed in a Halle oven. A quartz thermometer probe was mounted in the aluminum block enclosing the calcite (see Figure 12). The temperature was read out on a Hewlett-Packard (Dymec) Quartz Thermometer. The quartz thermometer is repeatable over the short term to $\pm .0005^\circ\text{C}$ and over times of days to $\pm .001^\circ\text{C}$. It is linear over the range used to $\pm .0008$ degrees per degree.

Shown in Figure 13 is an optical schematic of the test system. A 2 mm He-Ne collimated laser beam is sent through the filter and the output detected by a photometer. In addition to the laser beam, a solar beam can be simultaneously shone through the filter. The filter is tunable by rotating a half waveplate behind the entrance polarizer. Both the entrance and exit polarizers are mounted separately from the Halle oven.

As the temperature changes, the index of refraction difference and the length of the calcite changes, so that the laser line is alternately transmitted and extinguished. For this crystal there are approximately 2.22 transmission cycles/ $^{\circ}\text{C}$. Fractions of a cycle can be measured by rotating the half waveplate to an angle where a transmission minima occurs. The locations of transmission minima can be reliably located to one degree in angle, thus the equivalent temperature measurement accuracy is $\pm 1/90$ of $1/2.22$ or $\pm .005^{\circ}\text{C}$.

CHARACTERISTICS OF THE CONTROLLER

Four identical controllers were evaluated. Controllers were set to control at approximately 30°C , 36°C , 42°C and 48°C . In a normal room environment, all the controllers would maintain an oven temperature of $\pm .001^{\circ}\text{C}$ as indicated by the quartz thermometer readout. When the temperature reading of the quartz thermometer was stable, the laser transmission was also stable. The effects of thermal environment of the temperature controller itself was tested by separately placing the calcite oven and the temperature control electronics in a thermal chamber that could be cycled from 0° to 50°C . The temperature of the calcite oven changed by $-.0028^{\circ}\text{C}/^{\circ}\text{C}$ of ambient over the ambient range from 0°C to 50°C . The electronics caused a change of $.001^{\circ}\text{C}/^{\circ}\text{C}$ ambient. With precision components the temperature control system could be improved by a factor of at least two.

SOLAR EFFECTS ON OVEN TEMPERATURE

With the oven interior temperature well stabilized and the waveplate adjusted so that a transmission minima occurred for the laser beam, an f/17 solar beam was allowed to pass through the filter. The beam was prefiltered by a 8\AA three period blocker and an IR rejection filter. There was some tendency for the transmission minima to move a degree in angle or for the calcite to change by $.005^{\circ}\text{C}$ in temperature. However, after repeating the test a number of times, no statistical significance could be obtained for a shift of a degree.

To further test for evidence of solar heating, the 8\AA blocker was replaced by a 150\AA blocker which increased the flux by a factor of nearly 20. Again, there was some evidence of a change in angle of maximum extinction by a degree in angle. Hence, temperature change, if it exists, must be attributed to a minor IR leakage of the trim filter. In any case, the calcite changed by less than $.005^{\circ}\text{C}$ or $.00181\text{\AA}$ which is certainly not of any consequence.

TRANSIENT EFFECTS AND THERMAL GRADIENTS

By tracking the transmission of the laser beam as a function of time, it was possible to measure the temperature of the calcite as a function of time. To measure the temperature response on heating the oven was set at a control temperature using a temperature controller. The waveplate was rotated to obtain a transmission minima, and then a new temperature controller was attached to the oven. (Separate temperature controllers were used because each individual controller is tuned to control optimally at a specific temperature. The controller can be fine tuned over a one degree range.) During the heating period, the output of the laser was continuously recorded on a strip chart recorder. As the calcite heated, the laser transmission was modulated, a new minima occurring when the total phase change of the calcite changed π radians (one fringe).

When marks on the recorder chart were made at specific temperatures indicated by the quartz thermometer during the warm-up, a comparison of the thermal response of the filter oven and the calcite crystal was obtained.

A plot of oven temperature and calcite temperature versus time during a transition from 30° to 36°C is shown in Figure 14. As can be seen from the curve, there is almost a degree centigrade difference between the aluminum block and the center of the calcite during the heat-up phase. (The laser beam probed the calcite at its center.) For the run shown, the calcite was a press fit into the aluminum housing.

If the observed temperature difference was occurring across the calcite, about 2 fringes would have been observed along the aperture radius. Under illumination by a full aperture laser beam, the radial phase change would manifest itself by two concentric bright rings which continuously expanded out from the center of the crystal as the crystal heated. When illuminated by a full aperture collimated beam, no ring structure was observed during heat up. To check more quantitatively, the 2mm laser beam monitor was moved to pass through the calcite 1.5 mm from the edge of the crystal and then thermal cycle experiment was repeated. The response of the calcite at the edge was identical to the response at the center of the crystal. Thus, no thermal gradient exists across the calcite even under the fastest heat input condition of the controller, $.4^{\circ}\text{C}/\text{min}$.

To further check the location of the thermal gradient, the element was removed and thermal contact silicon grease was installed in the space between the crystal, its containing tube, and the oven block. The thermal cycle experiment was repeated. The grease reduced the gradient by a factor of two. The rest of the gradient most probably is across the aluminum tape that is wrapped around the calcite.

From the tests on the sample element it can be inferred that a shock mounted and space qualified calcite element would be isothermal, but that a temperature gradient would exist across elastomer mounting substance. The size of the gradient would be dependent upon the thermal input rate. In any case, such gradients can be measured and calibrated.

TEMPERATURE SENSITIVITY OF CALCITE

INTRODUCTION

The sensitivity of the operating wavelength of a birefringent filter to temperature is a critical parameter in the design of an active filter controller which corrects for temperature changes by tuning elements by rotation of polarizers or waveplates. A knowledge of the temperature sensitivity is also important for the design of a constant temperature enclosure. Somewhat surprisingly, the temperature sensitivity of calcite has not been measured with high accuracy or as a function of wavelength. The only published value being that of Lyot at the Sodium D line.

The thermal effect can be measured by two techniques. The first directly measures the change in wavelength of a transmission peak of a Lyot element due to a change in temperature. The second measures transmission modulation as a function of temperature at a fixed wavelength. The wavelength sensitivity is obtained from the transmission modulation through the relation

$$\frac{\partial \lambda}{\partial T} = \lambda^2 \frac{2\pi}{\phi} \frac{\partial \phi}{\partial T} \left[\frac{\lambda}{\left(1 - \frac{\lambda}{\mu} \frac{\partial \mu}{\partial \lambda}\right)} \right] \quad (1)$$

where

$$\phi = 2\pi \frac{\mu d}{\lambda} \quad (2)$$

and where μ is the index difference, d is the thickness of the crystal, and λ the wavelength. The change in phase, ϕ , with temperature comes from both change in index and crystal length. That is,

$$\frac{\partial \phi}{\partial T} = \phi \left(\frac{1}{\mu} \frac{\partial \mu}{\partial T} + \frac{1}{d} \frac{\partial d}{\partial T} \right) \quad (3)$$

Comparison of equations (1) and (2) shows that the temperature sensitivity is independent of crystal length.

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Measurements of both the thermal coefficient of expansion and of index are given in the International Critical Tables; however, they are not sufficiently accurate to determine the wavelength sensitivity. The index values have been fitted by a polynomial by Beckers which is accurate to a part in 10^5 - the accuracy of the index values. The temperature derivative term in the polynomial is on the order of 1×10^{-5} per degree, so that it is not surprising that the temperature sensitivity predicted by the critical values are not accurate to better than 10-20 percent.

To measure the shift in wavelength directly requires a very well calibrated high resolution spectrograph. Therefore, these experiments were carried out at Kitt Peak. To measure the modulation with temperature requires only stable wavelength sources and an accurate photometer. The modulation experiments were performed at Lockheed.

MEASUREMENT TECHNIQUES

In order to measure values of $\partial\lambda/\partial t$, a Halle filter oven was modified to contain a single calcite crystal. The crystal was a normal wide-field Lyot element with a separation between transmission maxima of approximately 1\AA . The oven temperature was monitored by the quartz thermometer. The temperature was controlled by a set of four Lockheed temperature controllers with nominal control temperatures of 30, 36, 40, and 48°C .

The filter was mounted vertically over the entrance slit of the main spectrograph of the McMath Solar Telescope at Kitt Peak National Observatory (which is a 13.7 meter Czerny-Turner with a spectral resolution 300,000). The filter was fed with an f/60 solar beam. Measurements were made by using the spectrograph in a spectrometer mode scanning over approximately 10\AA centered at 4702, 5150, 5850 and 6439\AA . A total of 12 scans were co-added for each measurement. At each of the wavelengths, a solar spectrum was taken before and after the measurements at the four temperatures.

The measurements at Lockheed were made using the system used for the thermal controller experiments, where the laser could be replaced by a line source

with a collimator and appropriate isolation filter (Figure 13). The line source measurements were carried out at λ 7032, 5461, 4800, 4678, and 4358. Laser measurements were made at λ 6328. These measurements used the 0.08Å calcite element - the element used in the thermal controller experiments.

KITT PEAK NATIONAL OBSERVATORY DATA REDUCTION

All of the raw Kitt Peak data were manipulated using a spectral data handling program called REDUCER. The spectral data were corrected for the grating equation, fourier transformed, filtered, and retransformed. The transform operations served to optimally smooth the data. The smoothed data were then analyzed to find all of the locations of intensity maxima and minima. The wavelength differences between corresponding minima or maxima on records made at different temperatures yielded $\delta\lambda/\delta T$.

The measured values for the temperature sensitivity did not show any temperature dependence. The results of the KPNO measurements are shown in Table IV. The least squares straight line fit through the data points is

$$\frac{\delta\lambda}{\delta T} = 7.35 \times 10^{-5} \lambda - .10273 \quad (4)$$

where $\frac{\delta\lambda}{\delta T}$ is in Å/°C and λ is in angstroms. The mean temperature is 39°C.

LOCKHEED DATA REDUCTION

The experiment at Lockheed directly measured the number of intensity cycles between two temperatures. Because the number of cycles could be obtained with high accuracy it was noted in the first measurements that the fringe count/°C was temperature dependent. Since even Lyot had stated that the temperature sensitivity

Table IV

Temperature Sensitivity of Calcite From KPNO Data

	$\frac{\partial \lambda}{\partial T} (39^\circ)$
4702	.2433
5150	.2771
5866	.3306
6439	.3704

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of calcite was independent of temperature from 18°C to 40°C, numerous measurements were made at each temperature in order to obtain good statistics.

Shown in Table V are the mean temperature and mean sensitivity as well as the least square fit straight line parameters for each of the measured wavelengths. Also shown in Table V are the total number of measurements at each wavelength. Using all the straight line fits of the fringe count per degree at the various temperatures, a mean temperature dependent straight line can be obtained for the fringe count.

$$F/^{\circ}C = \alpha_{\lambda} (1 + 5.88 \times 10^{-8} \lambda T) \quad (5)$$

The parameter α_{λ} is excellently fit by

$$\alpha_{\lambda} = 1.494 \times 10^4 / \lambda - .16443$$

Thus the number of fringes/ $^{\circ}C$ is

$$F/^{\circ}C = (-.16443 + 1.494 \times 10^4 / \lambda) (1 + 5.88 \times 10^{-8} \lambda T) \quad (6)$$

where λ is in angstroms and T in $^{\circ}C$. The values given in equation (6) agree with the experimental values to within 0.1% from $\lambda 4358$ to $\lambda 7032$. The length of the calcite element used in the experiment was 13.010 cm, so that the number of fringes/cm/ $^{\circ}C$ is

$$F/cm/^{\circ}C = (-.01264 + 1.1483 \times 10^3 / \lambda) \times (1 + 5.88 \times 10^{-8} T \lambda) \quad (7)$$

The fringe sensitivity times the free spectral range (peak to peak separation) is just the wavelength sensitivity to temperature. The free spectral range is

$$FSR = \frac{\lambda^2}{\mu d (1 - \frac{\partial \mu}{\partial T} \frac{\lambda}{\mu})} \quad (8)$$

Table V

Fringe Count Parameters and Temperature Sensitivity
of Calcite From Lockheed Experiment

	$F/^{\circ}C$	FSR (39°)	$\frac{\partial \lambda}{\partial T}$ (39°)	α_0	$\alpha_1 \times 10^4$	N
4358	3.31	.06575	.2176			8
4678	3.0646	.07887	.2405	3.034	7.76	24
4800	2.96	.08417	.2492			8
5461	2.602	.11524	.2999	2.568	8.712	35
6328	2.225	.1622	.361	2.197	7.114	60
7032	1.994	.20540	.4096	1.958	9.58	24

Note: 1) $F/^{\circ}C = \alpha_0 + \alpha_1 T$

2) N is the number of measurements

The FSR for a centimeter length calculated from the Beckers formula can be fitted to better than a tenth of a percent by

$$\text{FSR} = (-2.722 \times 10^{-1} - 1.5065 \times 10^{-6} \lambda + 5.9725 \times 10^{-8} \lambda^2) \quad (9)$$

The product of equations (7) and (9) represents an analytic expression for the temperature sensitivity with an accuracy of a tenth of a percent.

Thus, the final analytic approximation for the temperature sensitivity is

$$\frac{\partial \lambda}{\partial T} = (-3.126 \times 10^2 / \lambda + 1.711 \times 10^{-3} + 6.86 \times 10^{-5} \lambda - 7.55 \times 10^{-10} \lambda^2) \times (1. + 5.88 \times 10^{-8} \lambda T) \quad (10)$$

The temperature sensitivity and the number of fringes/cm/°C versus wavelength at 40° are shown in Fig.15. The FSR for a cm of calcite versus wavelength is shown in Fig.16.

Although it is not readily apparent from casual comparison of equations (4) and (10), the KPNO and Lockheed results do agree at 39°C for the region 4700 to 6500Å. Both above and below the KPNO range (4700-6500) the temperature sensitivity departs as can be seen on Figure 15.

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AUTOMATIC WAVELENGTH STABILIZATION

INTRODUCTION

The traditional source of wavelength drift in birefringent filters has been inadequate thermal control of the calcite. The temperature controller described above is adequate for control to better than $.005^{\circ}\text{C}$ for periods of weeks to months, which is more than adequate for ground based uses. However, for a universal filter with individual tuning controls on each element, automatic temperature compensation by tuning is possible. Automatic tuning has the advantage of eliminating the temperature controller electronics. Absolute wavelength calibration is also possible by reference to a laser.

LOCKHEED UNIVERSAL TECHNIQUES

The Lockheed Alternate Partial Polarizer Universal Filter (LAPPU) is the first filter system designed to operate without a temperature controller. Instead, temperature sensors are mounted adjacent to the calcite crystals and the elements are tuned to maintain wavelength based on the signals from the sensors and temperature sensitivity of calcite. (Some care has been taken in the design to make the filter respond slowly and uniformly to temperature perturbations.) Although additional software complexity is introduced to compensate for the lack of a stand-alone temperature controller, the software required is a relatively small addition to wavelength referencing and automatic filter assembly which are features which are useful if not necessary for a Universal filter.

For the purpose of auto wavelength referencing, a Helium-Neon laser beam is shown through the filter. The filter control computer can read the values of the laser intensity transmitted by the filter. This data is used by a control program which successively

rotates each element and estimates the position of maximum transmission. Each tuning element is set to its individual position of maximum transmission. Several iterations of the program are sufficient to optimally assemble the filter on $\lambda 6328$. Periodic use of the laser reference and auto-assembly guarantees that the filter is operating properly and is on wavelength.

In order to operate the filter at any other wavelength than $\lambda 6328$ either the laser is referenced or the current estimated setting of $\lambda 6328$ is used to set the locations of the waveplates. Since the temperature sensitivity is known to a part in 1000, the setting capability is better than a degree in angle for the widest element. Narrower elements have corresponding higher resolution. One degree accuracy corresponds to a wavelength setting accuracy of the element $\text{FSR}/180$.

Operationally, to go to a standard wavelength in the spectrum a table of angle offsets from $\lambda 6328$ is referenced. These values are corrected by the temperature state of the filter. That is

$$\theta_k^i = \theta_k^i(T_0) + \frac{180}{\text{FSR}_{6328}^i} \frac{\partial \lambda}{\partial T_{6328}} - \frac{180}{\text{FSR}_k^i} \frac{\partial \lambda}{\partial T_k} (T - T_0) \quad (1)$$

where $\theta_k^i(T_0)$ is the angular offset from $\lambda 6328$ of element i operating at wavelength k_i at the reference temperature T_0 , θ_k^i is the angular offset to which element i is driven to operate at wavelength k , and FSR_k^i is the peak to peak separation of element i at wavelength k . Any nearby wavelength can be obtained by rotating the components proportional to the length of the elements tuned. To maintain wavelength the angular positions are updated when a change in temperature is sensed. The angular change is

$$\Delta \theta_k^i = \frac{180}{\text{FSR}_k^i} \frac{\partial \lambda}{\partial T_k} \Delta T \quad (2)$$

At present analytic approximations for FSR_k^i and $\frac{\partial \lambda}{\partial T_k}$ exist. Analytic expressions for the now tabulated values of $\theta_k^i(T_0)$ will be developed. They can be easily obtained by feeding the filter with a solar beam on the spectrograph bench and using a

version of the wavelength reference auto assembly program that obtains intensity data from the spectrometer output. The only requirement is that the spectrograph is set in the continuum.

MEASUREMENTS

Using the laser reference system built into the Lockheed Universal filter each element was successively spun and the position of maximum transmission measured. After each spin operation, the particular filter tuning element was set to the position of maximum transmission. This operation was carried out continuously for 6 hours. All spin data was stored. This included the set position of all elements, the transmission at the set point, and the transmission as a function of angle for each element. After each spin sequence, the filter was set to the position of $\lambda 6328$ predicted by the temperature compensation program. A comparison of the predicted position and the spin set positions yields the relative error of the temperature compensation routine.

During the testing, all stepping motors were always on, even if not stepping, and the filter was enclosed by a box. In a six hour period the interior temperature of the calcite increased from 20°C to 43°C . During the entire period the difference between the setting of the filter based on the thermal compensation program and the measured setting on the laser line was dominated by the least count errors of the thermal sensors. Ignoring least count effects the filter stayed on wavelength to within $.01\text{\AA}$ for the entire period.

The test described above is much more severe than ever would be encountered in normal operation. If the filter is not enclosed in a box, the interior temperature does not rise significantly. Normal operation would not operate the motors on much more than a five percent duty cycle.

RADIATION EFFECTS

The radiation problem for birefringent filters comes from two sources. One is the incident solar optical radiation and the other is the penetrating particle and X-ray flux.

Because of the sensitivity of the required blocking filters to solar radiation below 4000\AA and the leakage of polarizers above 7500\AA , the entrance windows must limit the solar optical flux to the $4000\text{-}7500\text{\AA}$ band. The filters used by the Skylab H-alpha telescope accomplish this and should be used in front of the birefringent filter. The solar flux behind the Skylab type filter is just the same as normally used on ground-based telescopes.

Penetrating radiation will have to traverse at least 3 cm of aluminum when incident from the side of the filter housing. Radiation along the axis of the filter will have all the optics and the secondary mirror structure in the path which will be greater than the equivalent of 3 cm of aluminum. Measurements of the radiation dose indicates that in a 330 nautical mile polar orbit the dosage is well described by

$$\text{Dose} = 27.410^{-t/.19} \text{ rads/day}$$

where t is in cm of aluminum. Radiation dose in a shuttle orbit would be less than this. This relation was obtained by E. Gaines (LMSC) based on data from Trapped Particle Environment of SMM, GSFC X-601-76-97. For a thickness of 3 cm of Al, the dose is

$$\text{Dose (3 cm)} = 3 \times 10^{-15} \text{ rad/day.}$$

Radiation damage occurs in polymer, crystals, and glasses at a radiation dose of 10^5 to 10^7 rads (Space Materials Handbook, Addison-Wesley, 1965).

From the above numbers the likelihood of damage to any of the materials inside the housing is very small.

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SUMMARY AND CONCLUSIONS

The basic direction of this study has been guided by the desire of the Quick Reaction and Special Purpose Facility Definition Team for feasibility data on a birefringent filter system for an H α /magnetograph telescope. The primary requirements were for a 1/6 \AA or narrower filter that was tunable from H α to a suitable magnetically sensitive line or lines in the visible. The two principal unresolved problem areas for a space qualified filter were proper shock mounting for the calcite filter elements, and wavelength stability. This study has developed a prototype tunable filter module which has survived the shuttle shake specification.

Experience has shown that the primary cause for wavelength instability is temperature induced wavelength shifts. Tests of the Lockheed temperature controller demonstrate sufficient temperature stability for a facility magnetograph. Tests of the Lockheed Universal filter using thermal sensors on the calcite elements and a software program to control the tuning components have shown that it is possible to temperature compensate without a hardware temperature controller. An advantage of the software system is the ability to incorporate a wavelength reference He-Ne laser to periodically verify the state of the filter. The complete software system for wavelength tuning, thermal control, and wavelength reference can easily be contained by a small sophisticated desk calculator such as an HP 9825. Further studies of the Lockheed Universal filter have shown that with a knowledge of the wavelength dependence of temperature it is possible to actively tune a filter to any desired wavelength with sufficient accuracy ($> .01\text{\AA}$) without a hardwired temperature control.

A secondary concern of this study has been the possibility of leakage of index matching oil from the filter. An oil sealed container with a novel rotary feed-through has been constructed and environmentally tested and demonstrated not to leak.

Oil filled versus non-oil filled filter designs have been evaluated. Optical cementing techniques have been developed which allow the majority of

the filter components to be mounted in groups, thus minimizing the number of air-glass interfaces. Calculation of cemented-A-R coated filter designs have shown that it is practical to eliminate the oil in a birefringent filter. A production grease-filled Halle HQ filter has been disassembled and reassembled with cemented components and A-R coated surfaces, but without oil. The A-R-cemented filter performs satisfactorily. Recently announced A-R coatings should allow operation from .35 to 2 microns without oil.

The modular approach to filter design and construction illustrated by the prototype filter module and the Lockheed Universal filter allows the construction of filters of any full width at half-maximum (FWHM) and free spectral range (FSR). Limitations on the full width at half-maximum are imposed by length of calcite. However, the existing Lockheed Universal has a FWHM a factor of three narrower than that desired by the FDT. The FSR is limited only by the number of modules used. The state of the art in blocking filters requires six to eight modules for a magnetograph system.

As a result of the work performed in this study, in the opinion of the authors, a tunable birefringent filter suitable for flight is now within the state of the art. However, A-R coated filters are limited to the range of the A-R coating.

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APPENDIX I

The purpose of this appendix is to record my (A.M. Title) judgement on material and techniques for producing birefringent elements.

1. Calcite

At present there seems to be at least four sources of calcite. The calcite comes from mines in Mexico, South Africa, India, and perhaps the USA. We have contacted a half dozen agents and have obtained prices in the range of \$750 to \$2000 per kilogram. The calcite in the Lockheed Universal, as well as all the Spectra Optics filters, has come from Mexican mines represented by Gary Anderson. Karl Lambrect Company sells both Mexican and South African calcite. We have obtained a sample of the South African material and it is of significantly higher whiteness of any previous Mexican calcite. Lambrect claims to have a significant stock of such material and guarantees its quality at \$2000 1 kg.

Harry Ramsey has had extensive conversations with representatives or owners of calcite mines and sample calcite has been examined. If high quality calcite exists, there is no reason to look further for alternative materials. It would appear prudent therefore to have someone knowledgeable about calcite and calcite working actually visit and examine to known mined stock piles to assess the claims of the mine owners and their representatives. Most critical is the stock of mined South African calcite, since this material, because of political problems, could rapidly become unavailable. In view of the high quality of the samples in hand, it is my opinion that sufficient calcite can be obtained.

2. Metal Acid Pthalates

The most attractive alternate crystal appears to be potassium acid pthalate (KAP) or one of its alkali metal relatives. These crystals have been grown in fairly large sizes and have an effective birefringence nearly that of calcite. We have some of the crystals produced at New Mexico State

and found them to be of non-uniform birefringence. These crystals are water soluble, fragile, and extremely sensitive to thermal shock.

At present, I feel that investigating KAP and its relatives is a lower priority than the plastic materials discussed below.

3. Plastic Materials

Polyvinyl alcohol (PVA) is a major commercial plastic. It is the plastic film base material for Polaroid Corporation polarizer and waveplate sheets. PVA becomes birefringent when stretched. Reasonable stretches yield birefringencies up to three times quartz. The plastic can be stretched very uniformly. The sheet material can be laminated to form birefringent elements. We have made a 80\AA tunable filter using PVA sheet. The sheet and the laminate are scatter free and are obtainable in at least 15 cm diameter.

PVA sheet should be considered for the purpose of making tunable pre-filters for the final filter. Solc type filters become much more attractive using laminate sheets. I would recommend looking into the Universal blocking filter using plastic sheet.

4. Michelson Elements as Analog Lyot Elements

Evans in 1949 suggested that Michelson interferometers could be used to build Lyot filters. The response of a fixed Michelson is identical to that of a Lyot element. A fixed wide field Michelson offers two significant advantages for elements narrower than $1/4 \text{\AA}$. First, since a Michelson is roughly cubical regardless of its effective FWHM for elements narrower than $1/4 \text{\AA}$, there is increasing greater length advantages. Second, a wide field Michelson has a field of view which is the square of the field of an identical bandpass wide field Lyot element.

We have built a prototype $1/20 \text{\AA}$ polarizing wide field Michelson. The device is quite stable and easily tuned by rotation of a waveplate or polarizer. a $1/50 \text{\AA}$ filter using 2 or 3 wide field Michelsons is a reasonably straightforward development.

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In my opinion, a $1/50 \text{\AA}$ tunable filter could almost eliminate the need for high dispersion spectrographs. It would provide an enormously powerful tool for line profile analysis and magnetic field strength.

FIGURE CAPTIONS

- Figure 1 Pallet random vibration levels.
- Figure 2 Filter random vibration levels.
- Figure 3 Fringe patterns visible in preliminary test unit due to separation of waveplates.
- Figure 4 Mechanical drawing of Mark I and II Preliminary Test Unit (dimensions in cm).
- Figure 5 Photograph of Mark II Preliminary Test Unit and mounting fixture for shake table.
- Figure 6 Mechanical drawing of prototype filter module (dimensions in cm).
- Figure 7 Photograph of prototype filter module prior to assembly.
- Figure 8 Exploded photograph of prototype filter module and sealed enclosure.
- Figure 9 Photograph of assembled sealed enclosure.
- Figure 10 Transmission versus number of modules for several values of reflection loss per surface.
- Figure 11 Reflection coefficient (full scale one percent) versus wavelength for a simple four layer A-R coating. Properties calculated using a published (Thetford, Optica Acta 11, 159, 1969) design and program thin film.
- Figure 12 Drawing of Halle oven showing location of the quartz probe and controller sensors.
- Figure 13 Optical schematic for the thermal controller test system.
- Figure 14 Temperature response of the quartz probe (oven) and calcite interior versus time.
- Figure 15 Temperature sensitivity and fringes/cm/ $^{\circ}$ C versus wavelength at 40 $^{\circ}$ C.
- Figure 16 Free spectral range versus wavelength for a one centimeter calcite element.

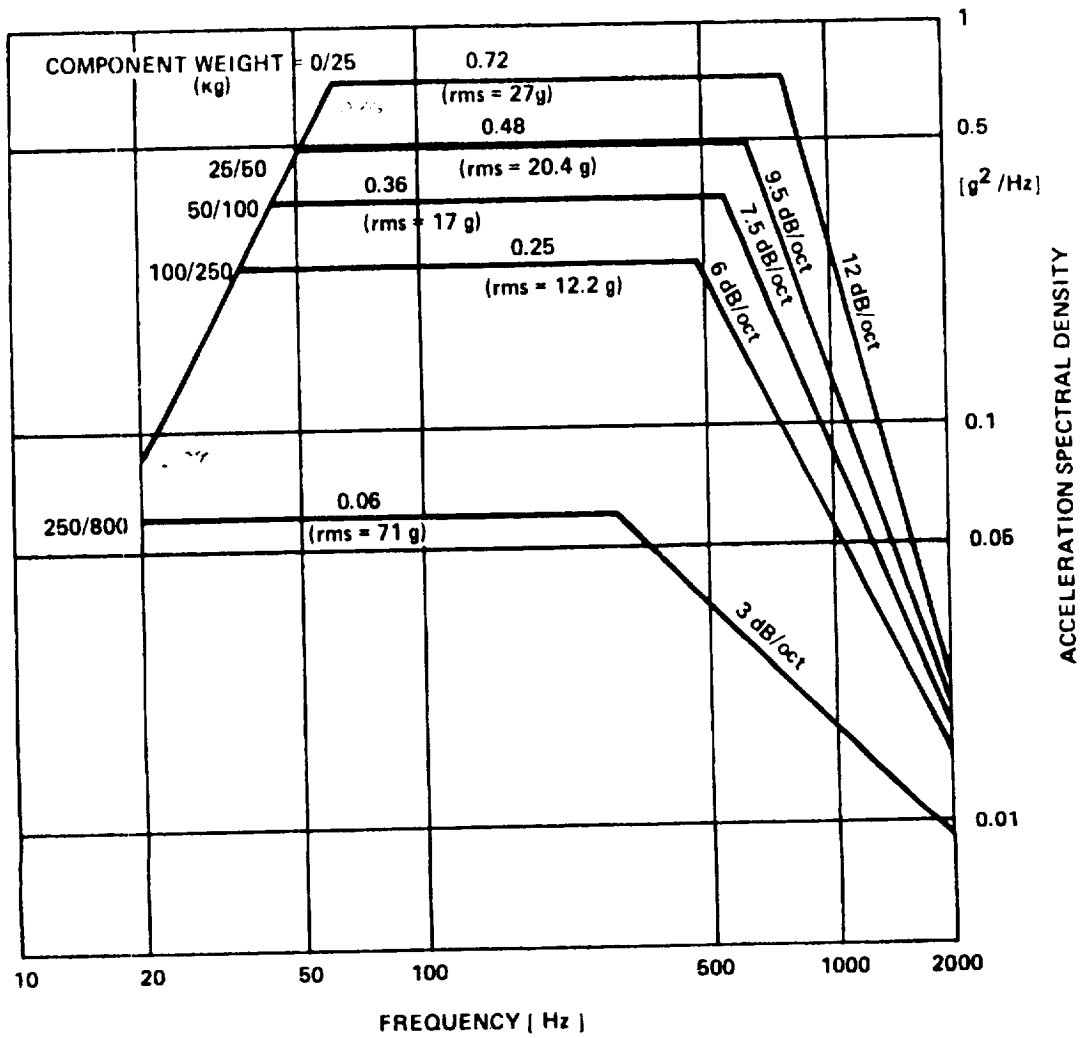


FIGURE 1

PALLET RANDOM VIBRATION LEVEL

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RUN NO.- 6

DATE: 3 17-76

TIME- 1101

FIXTURE L1

SPECIMEN ~~1X~~

AXIS- Z

GRMS- 27.2

I.D.- ReFrig Filter

F.S.- 1.0 G²/HZ

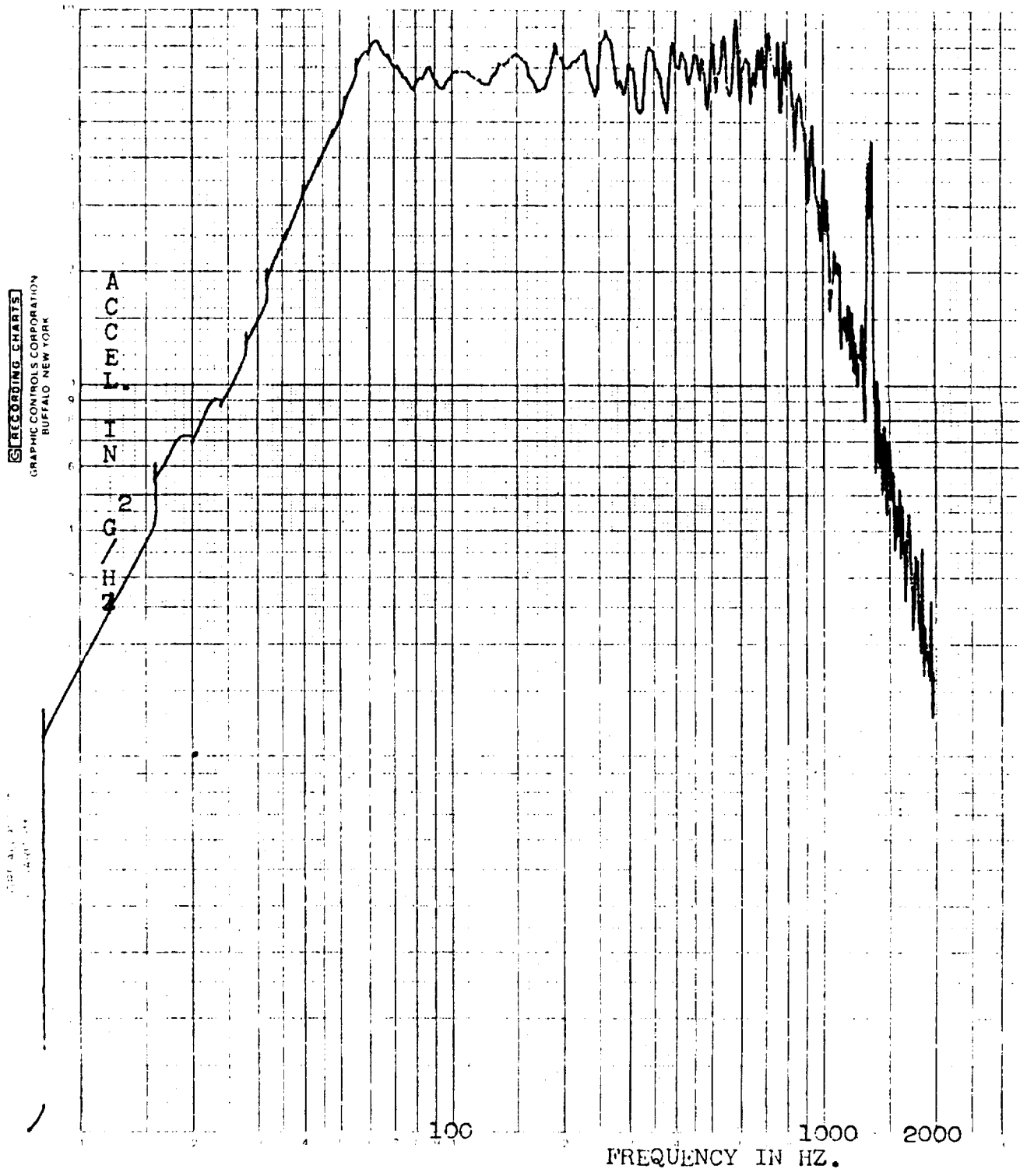


Figure 2

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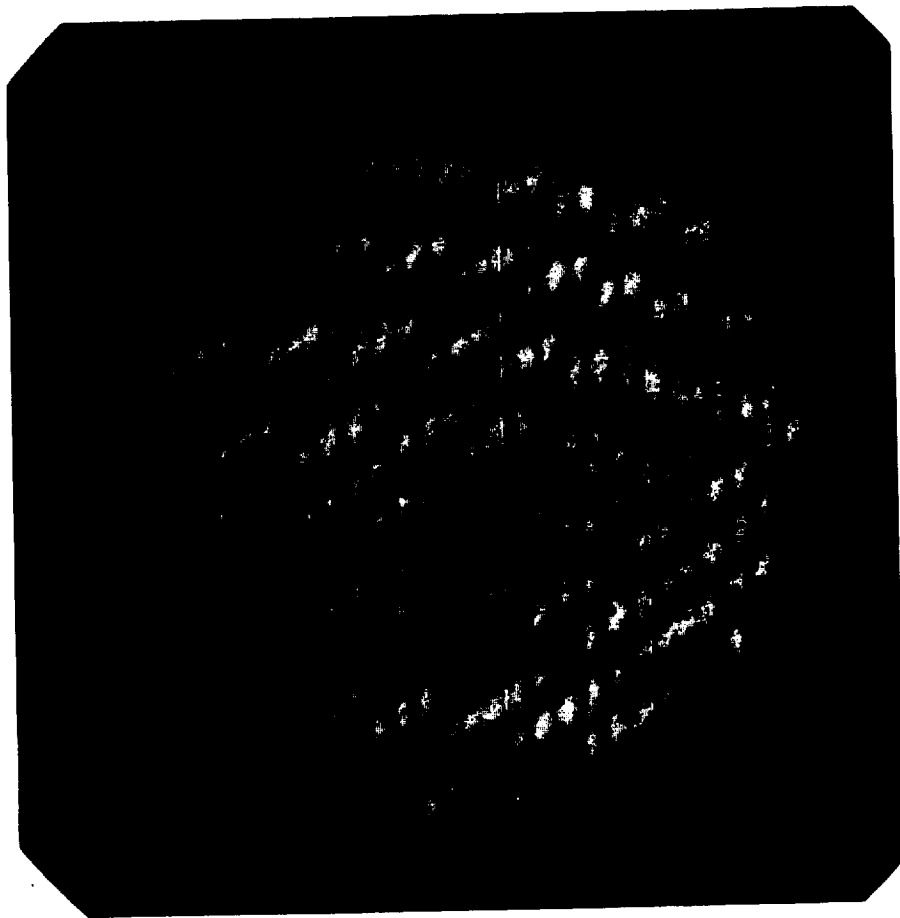


Figure 3

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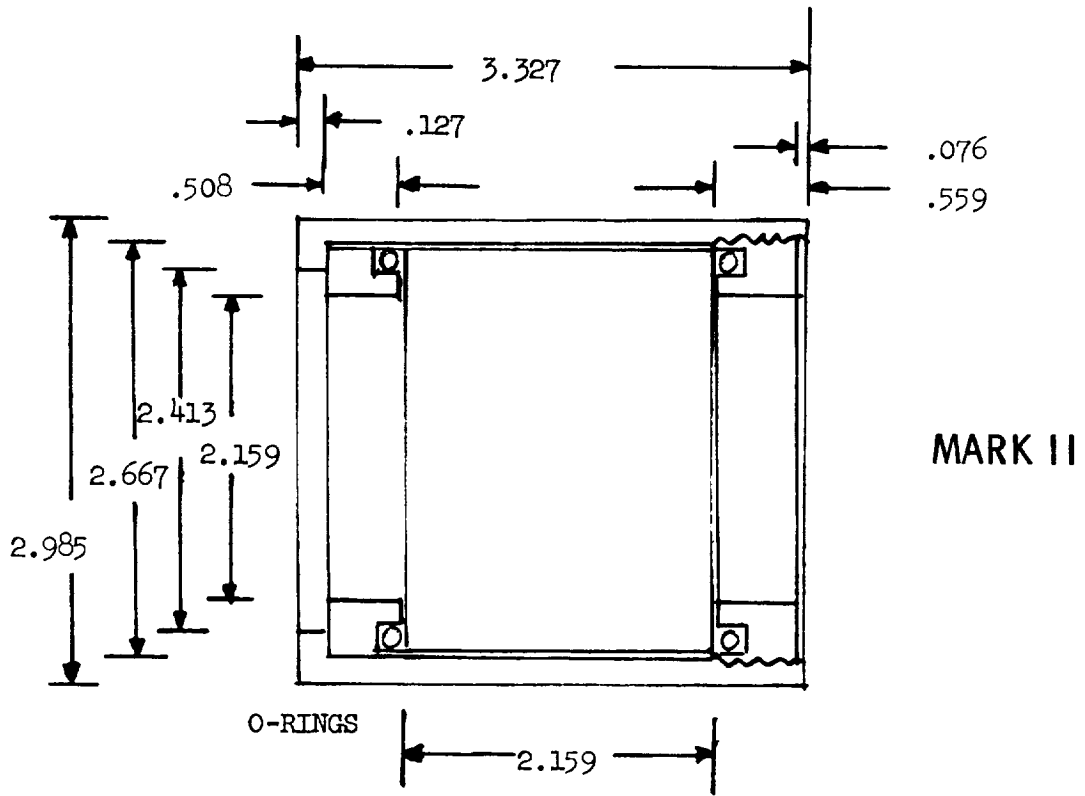
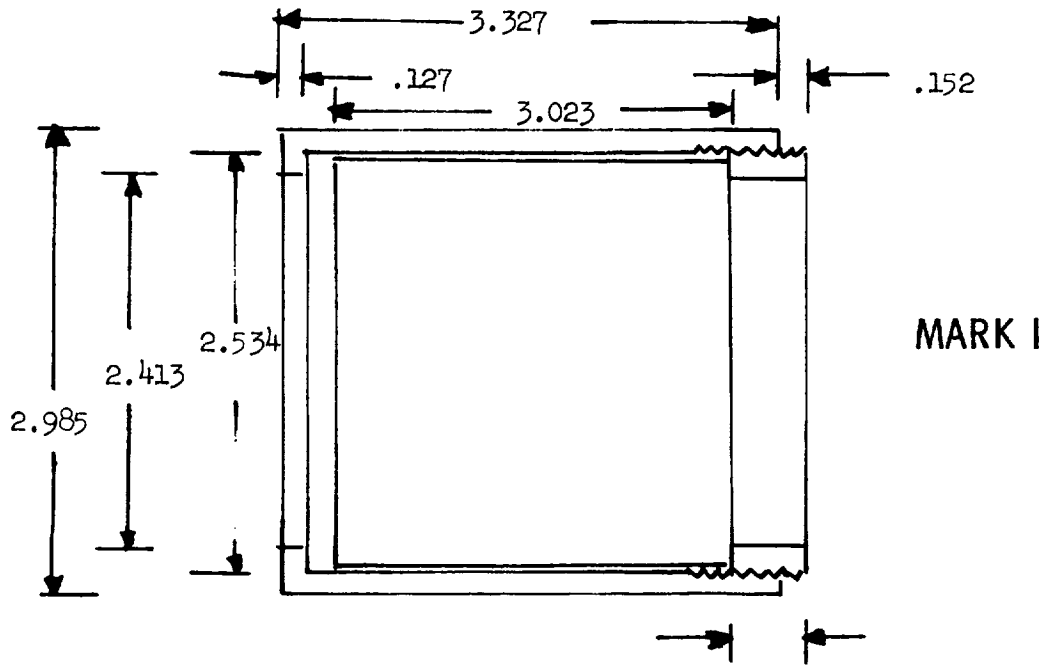
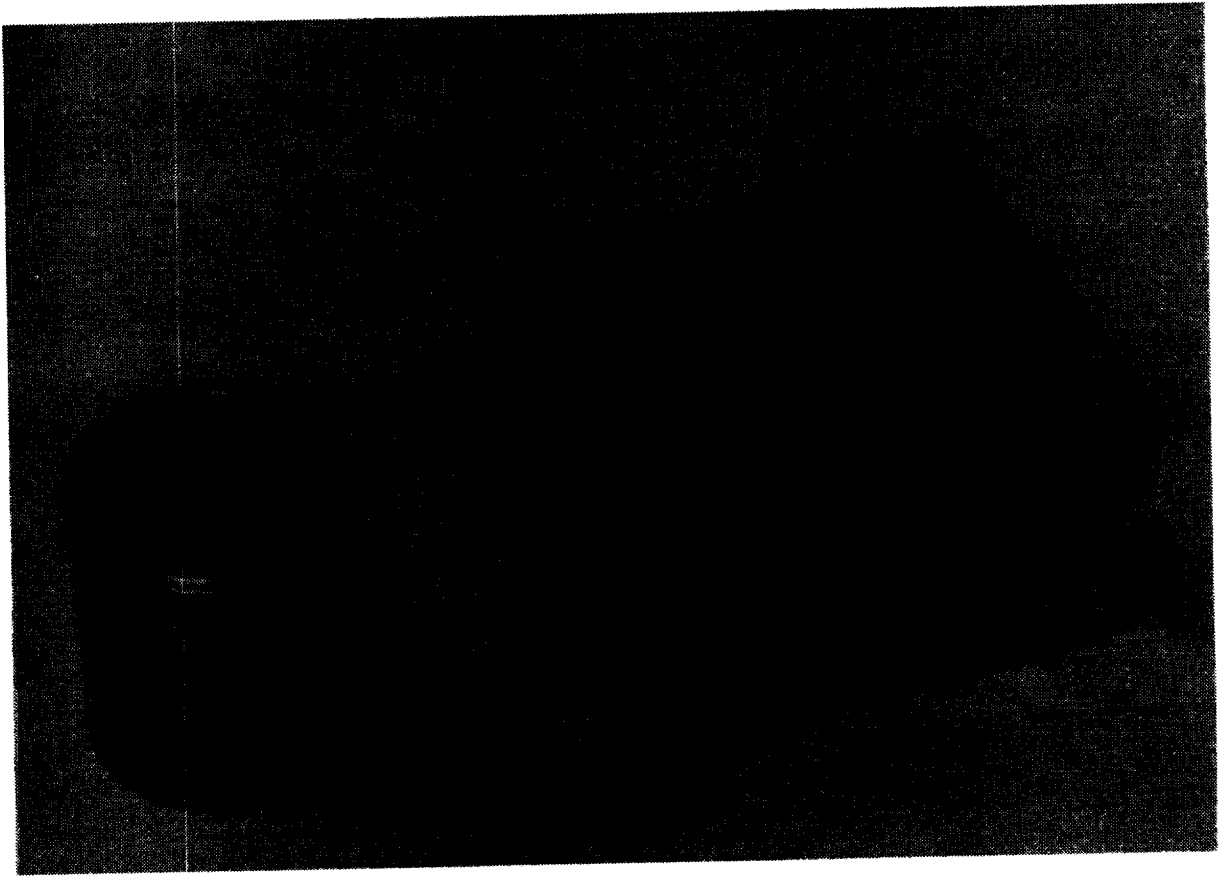


Figure 4



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Figure 5

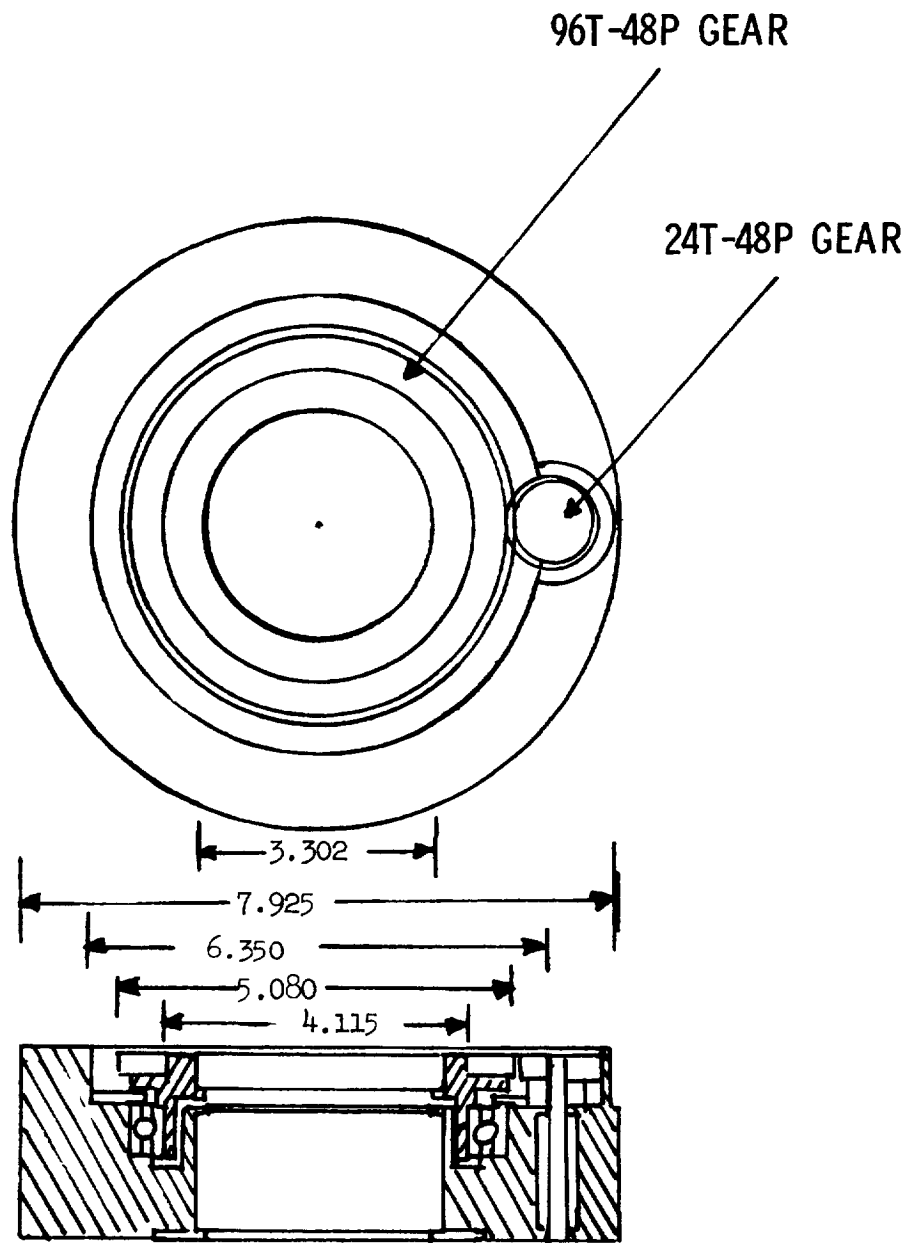
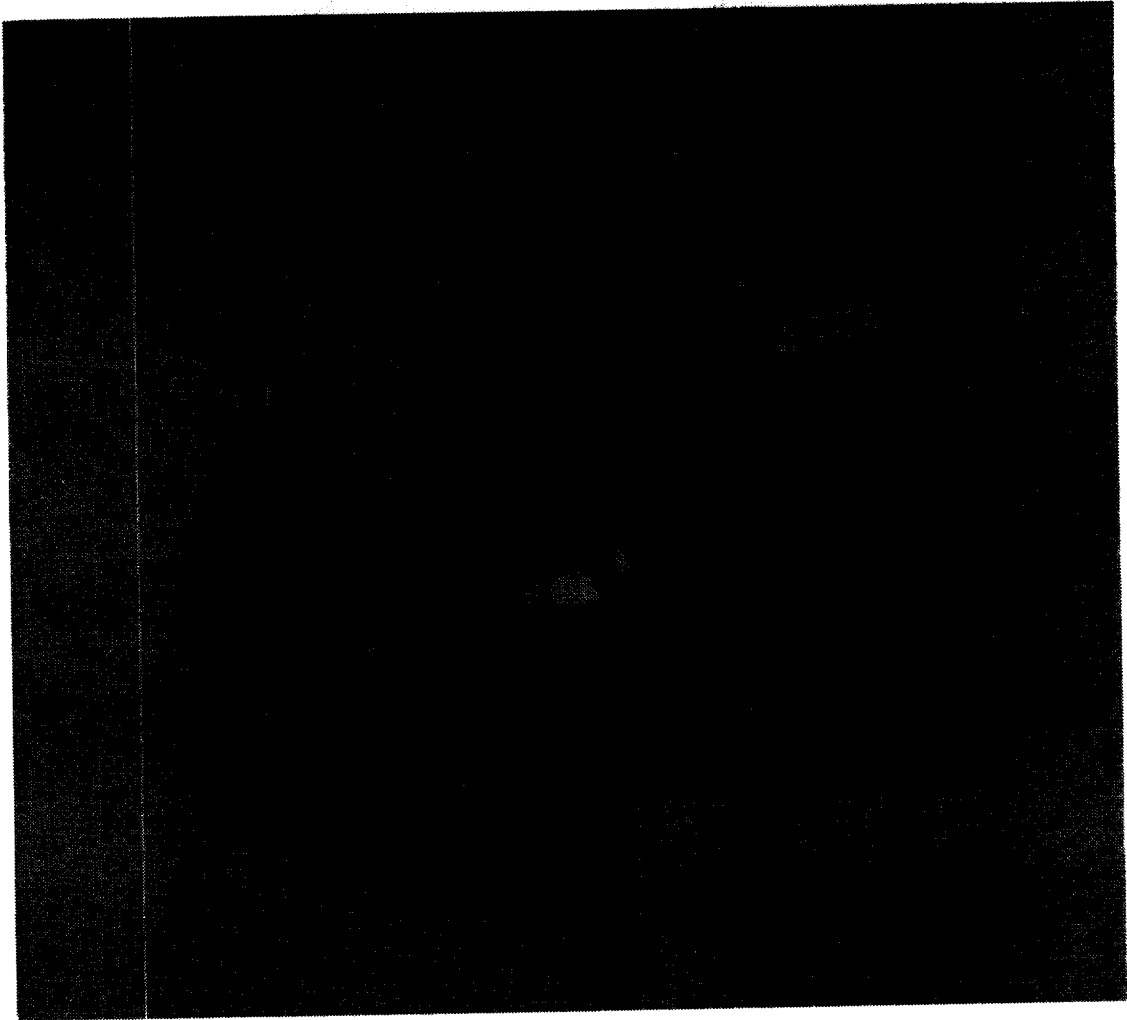


Figure 6



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Figure 7

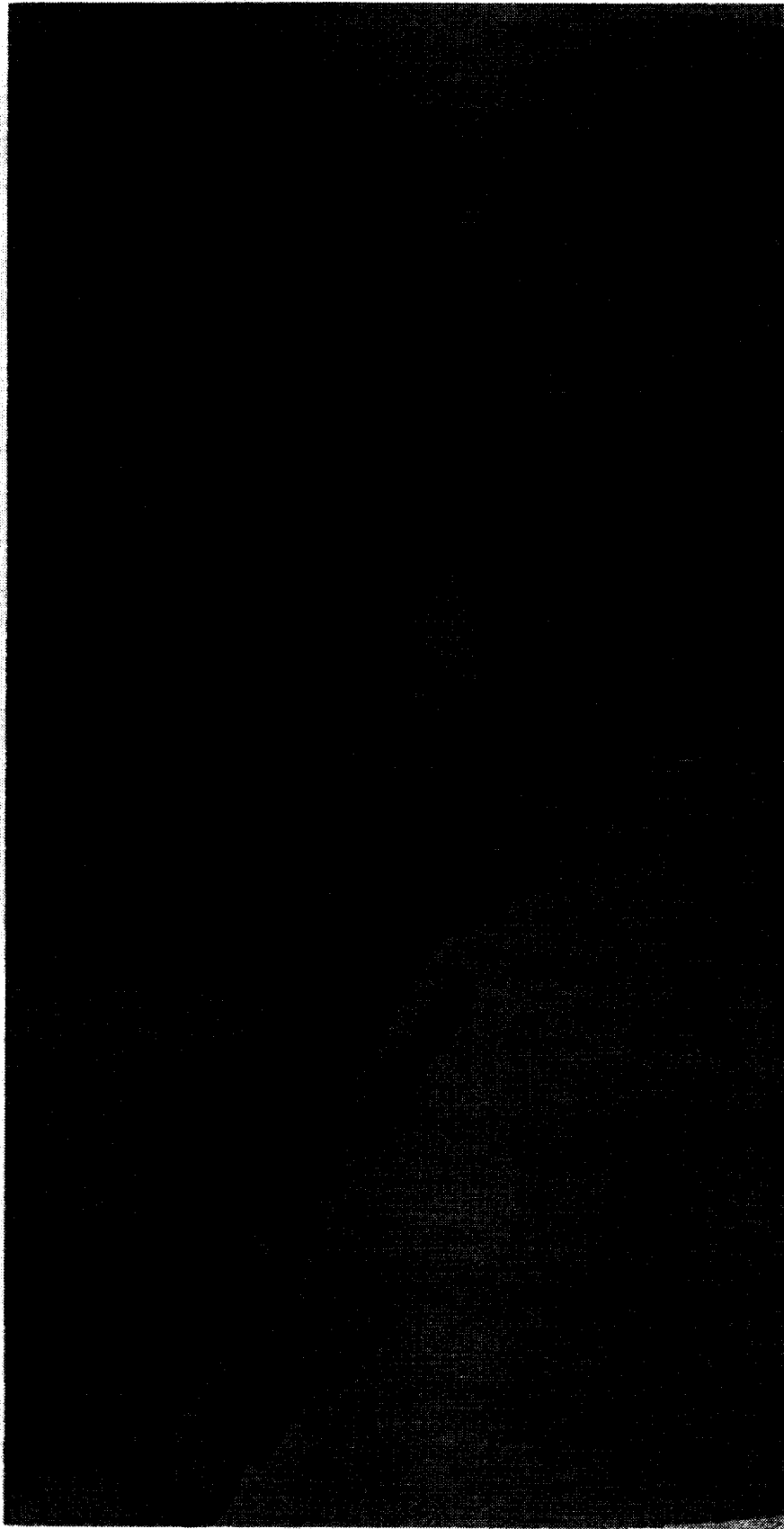


Figure 8



Figure 9

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Figure 9

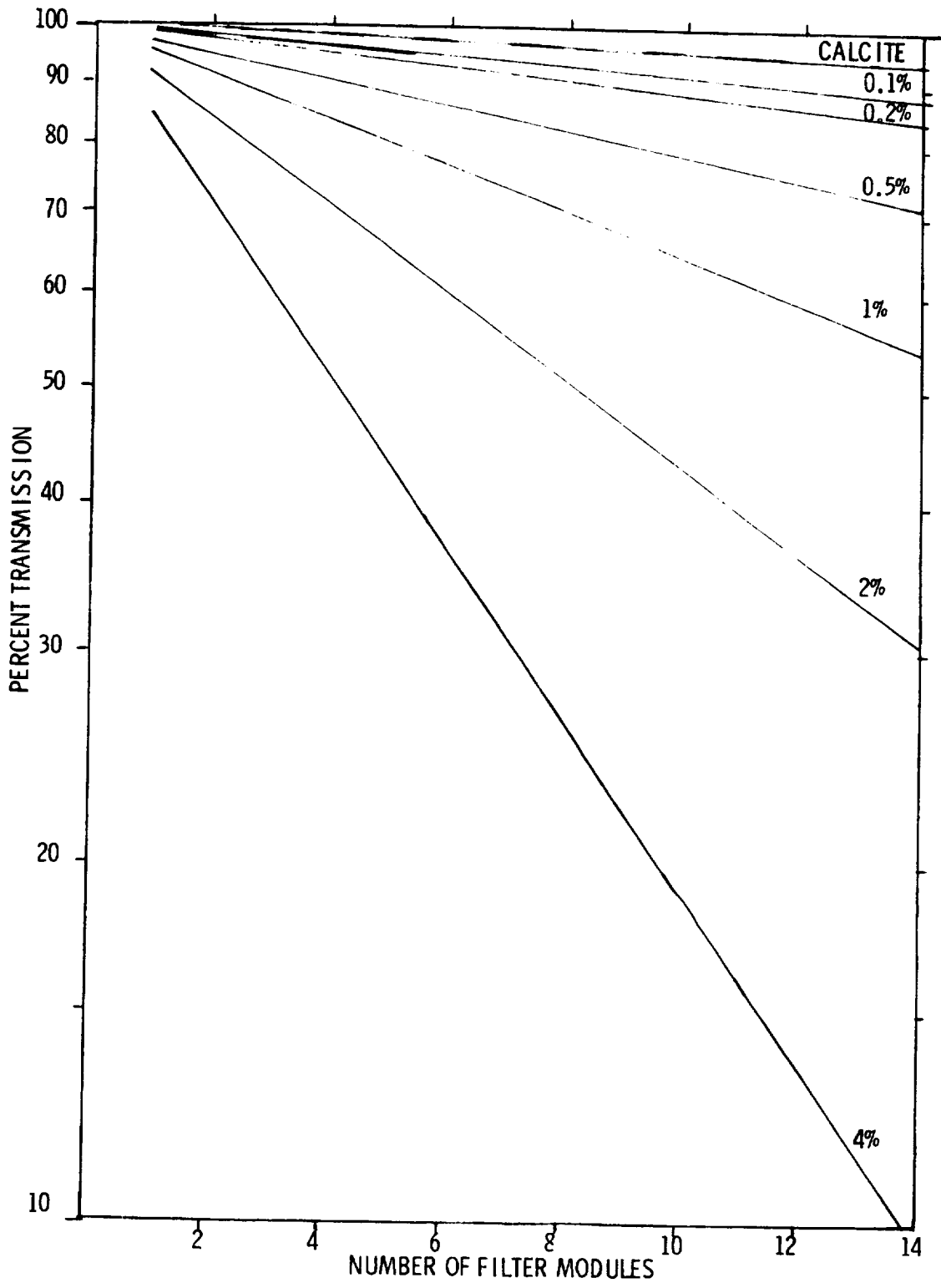


Figure 10

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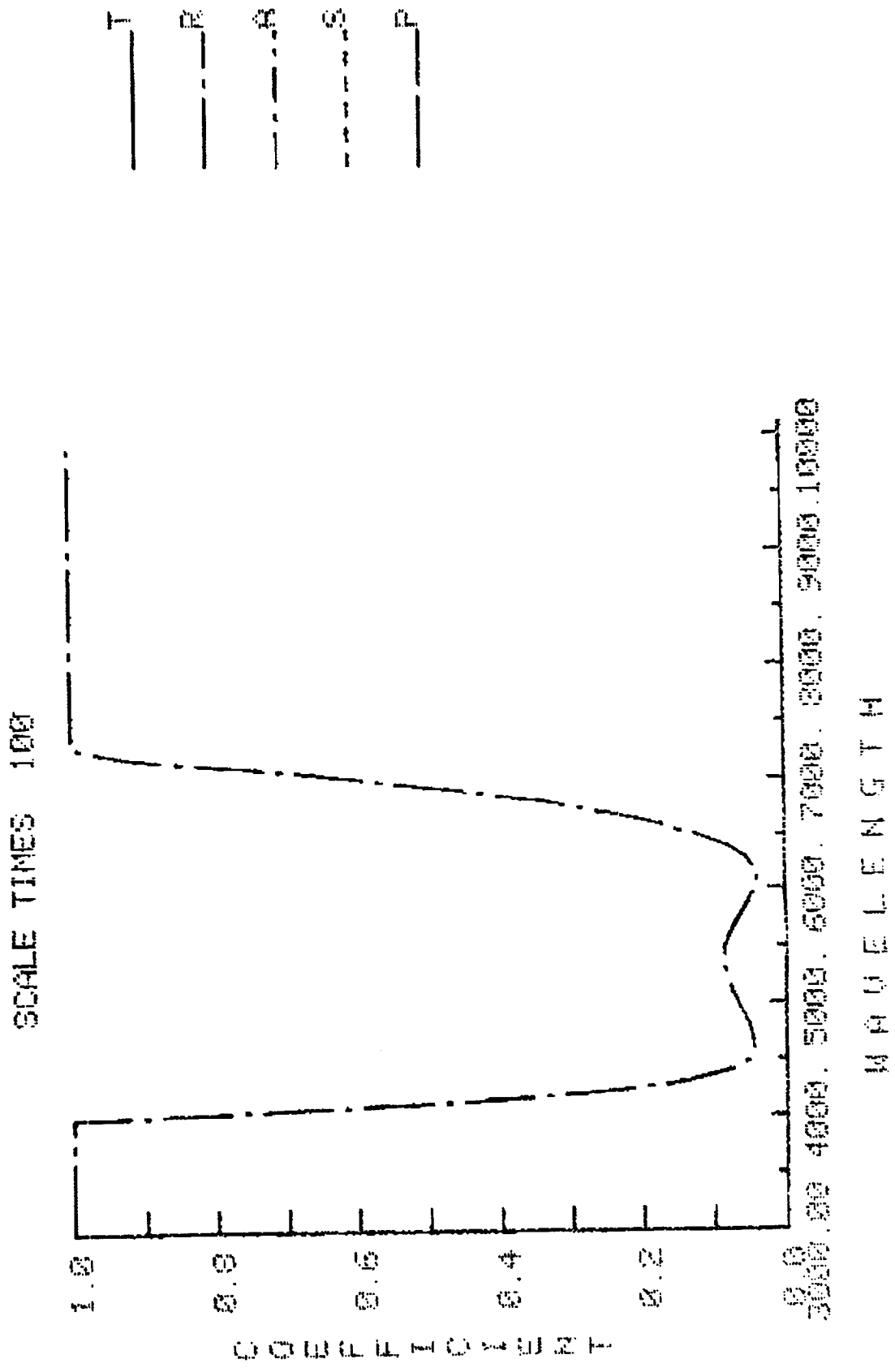
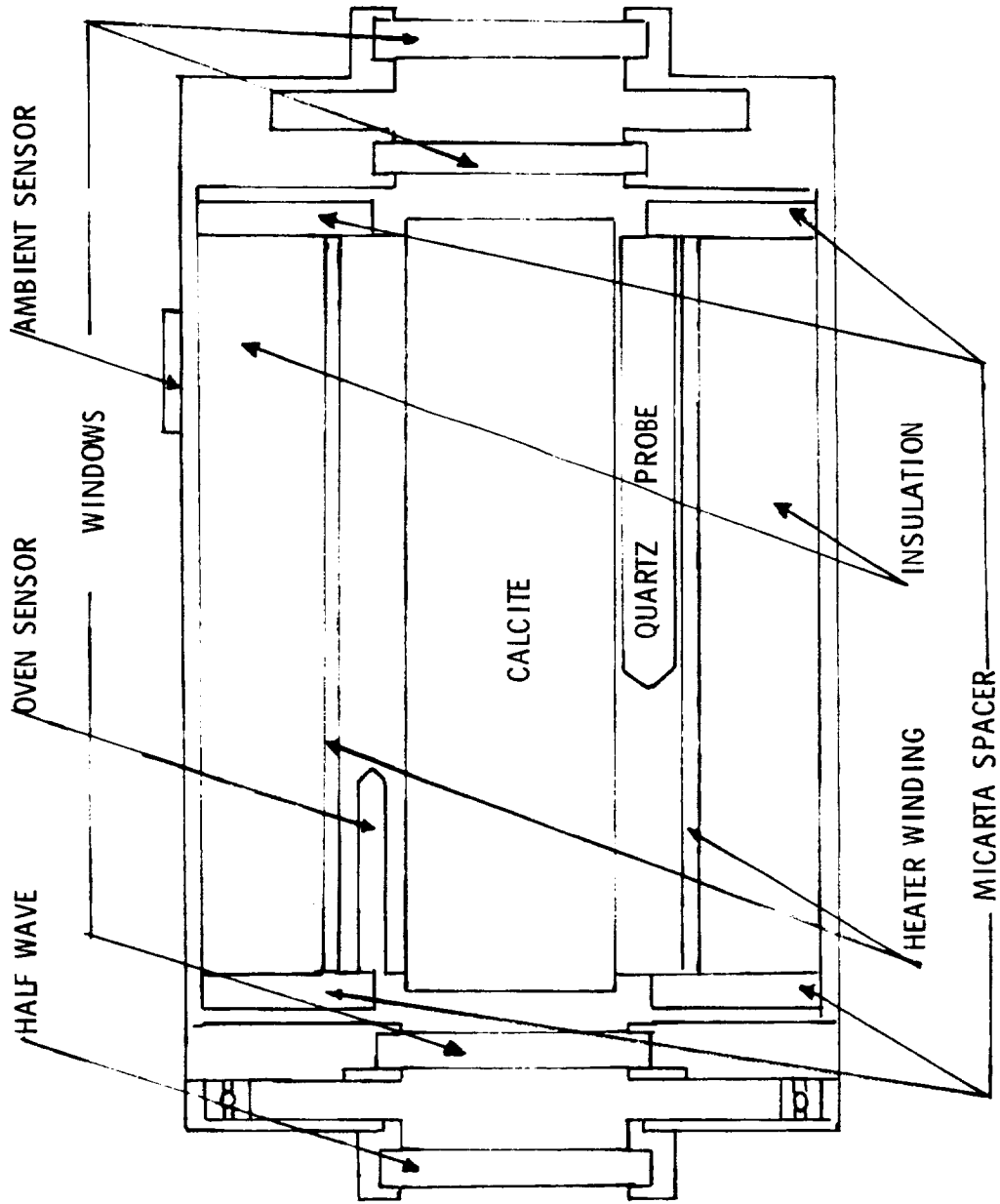
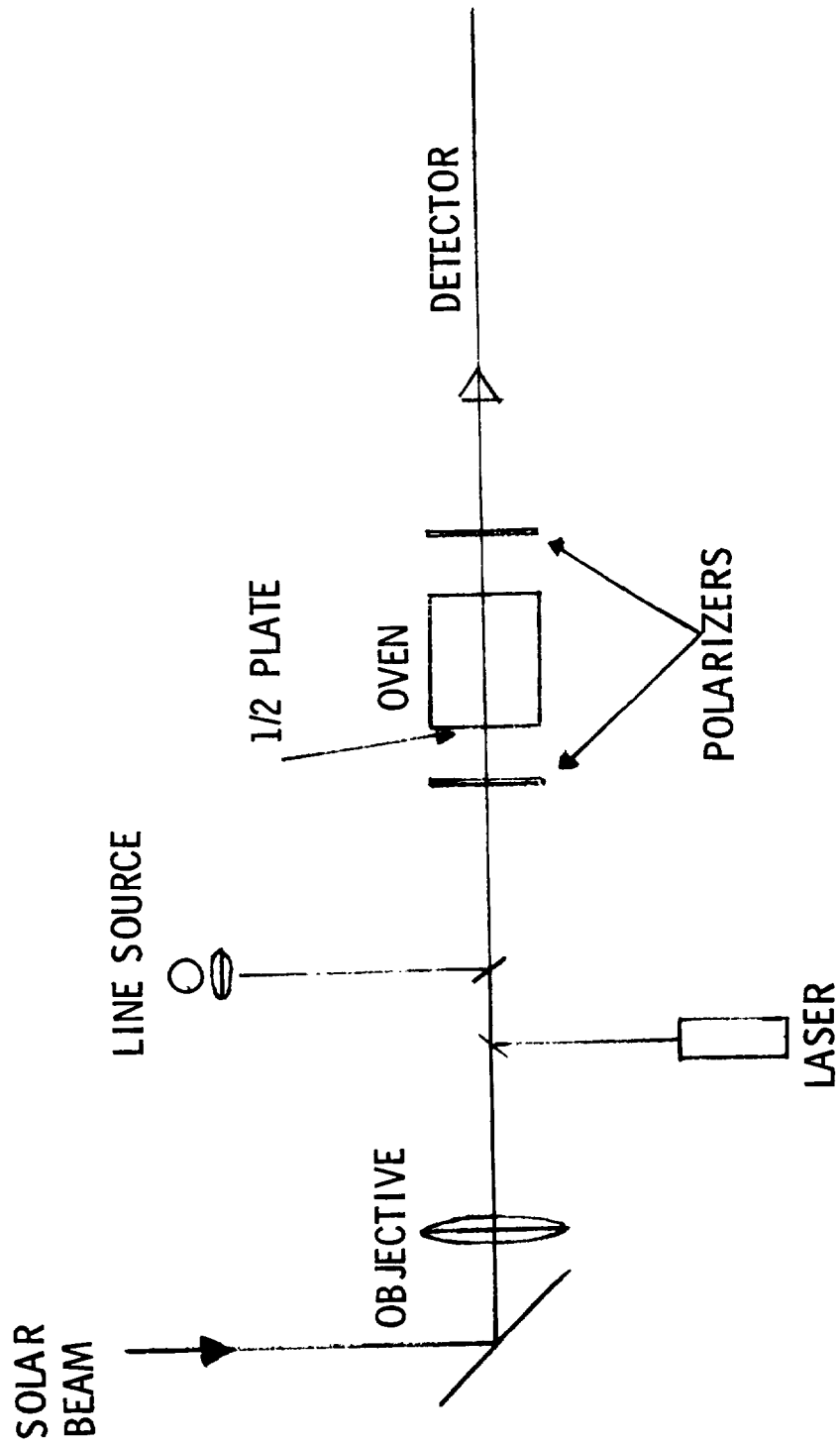


Figure 11



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Figure 12



OPTICAL SCHEMATIC

Figure 13

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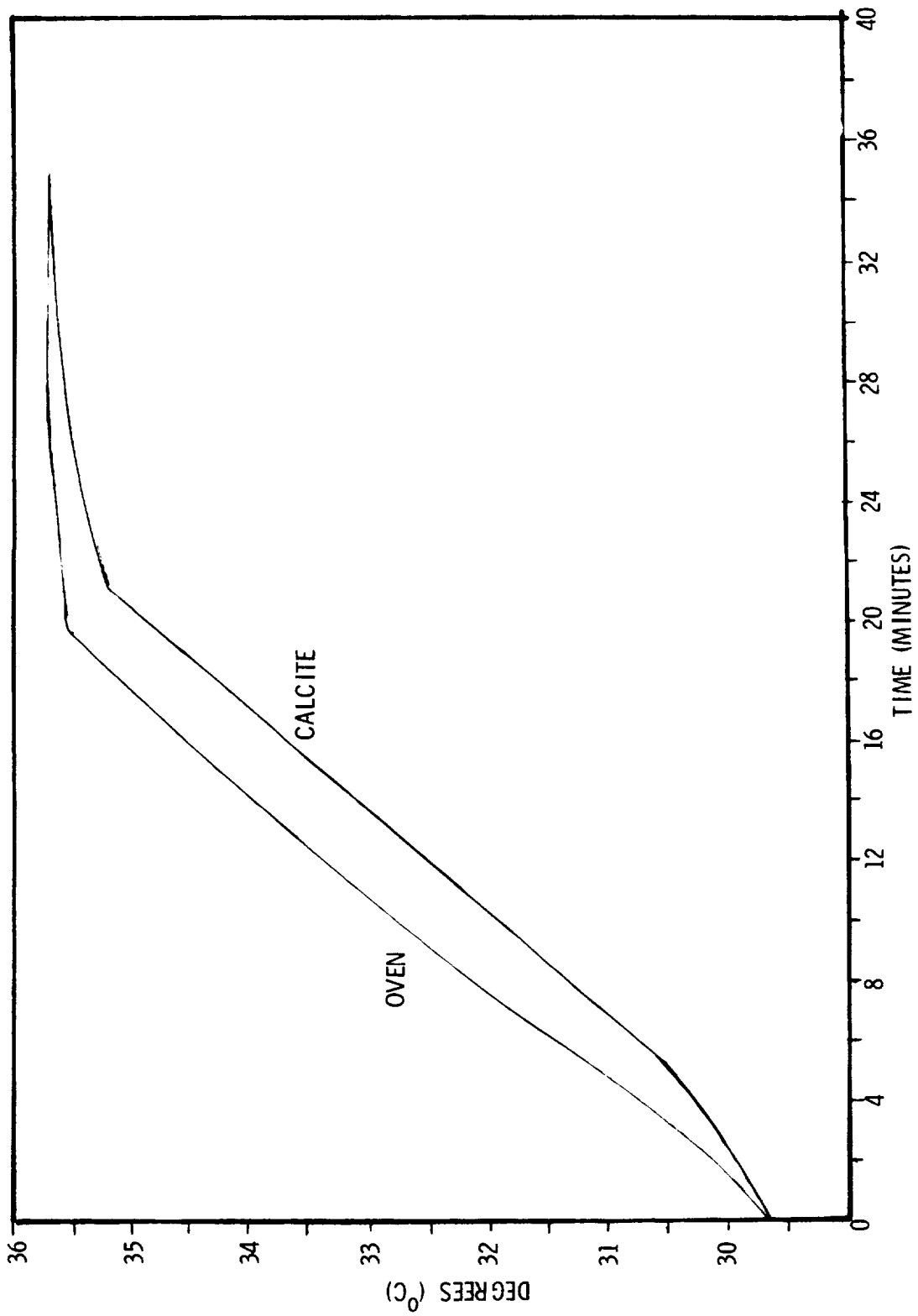


Figure 14

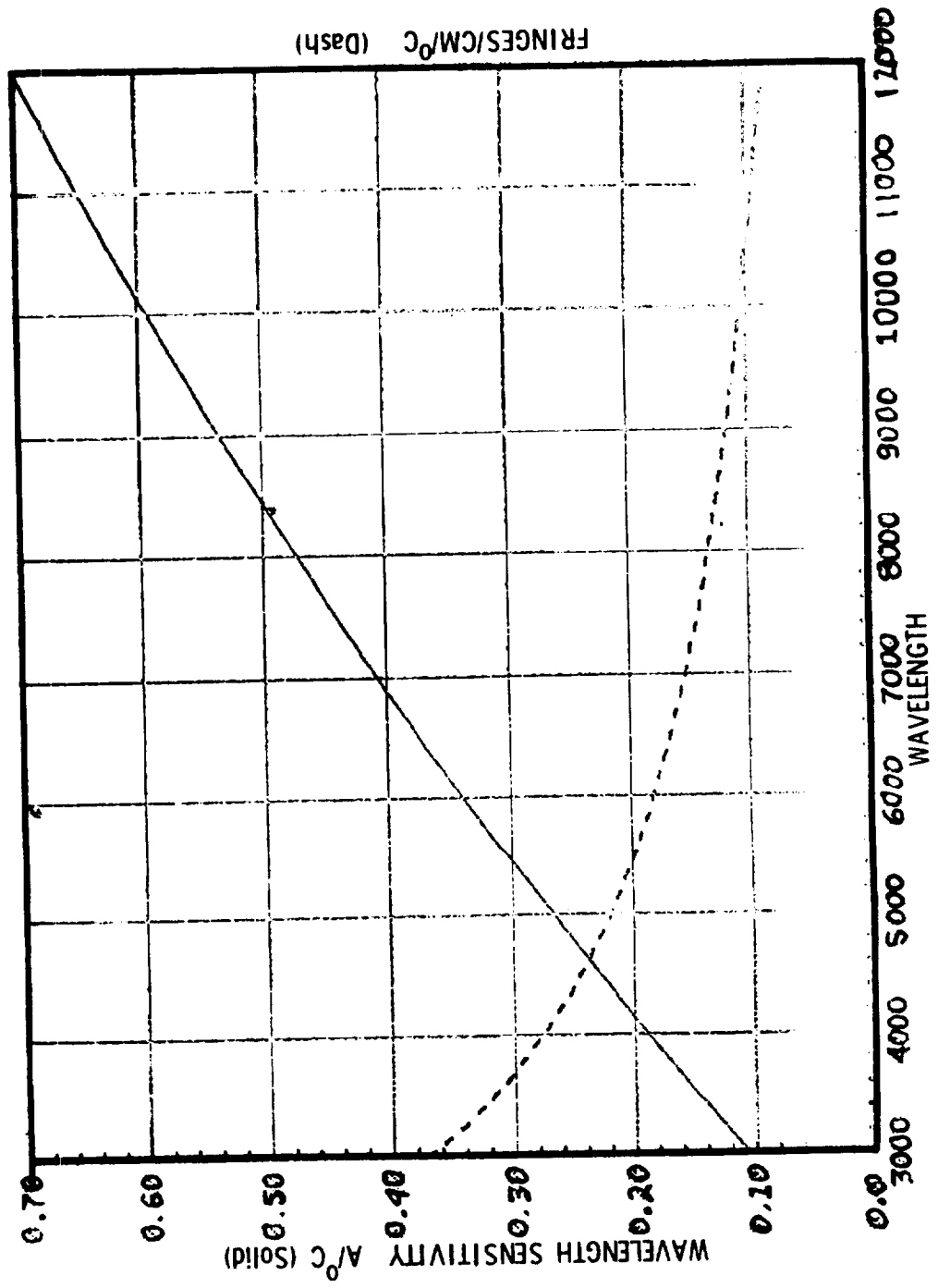


Figure 15

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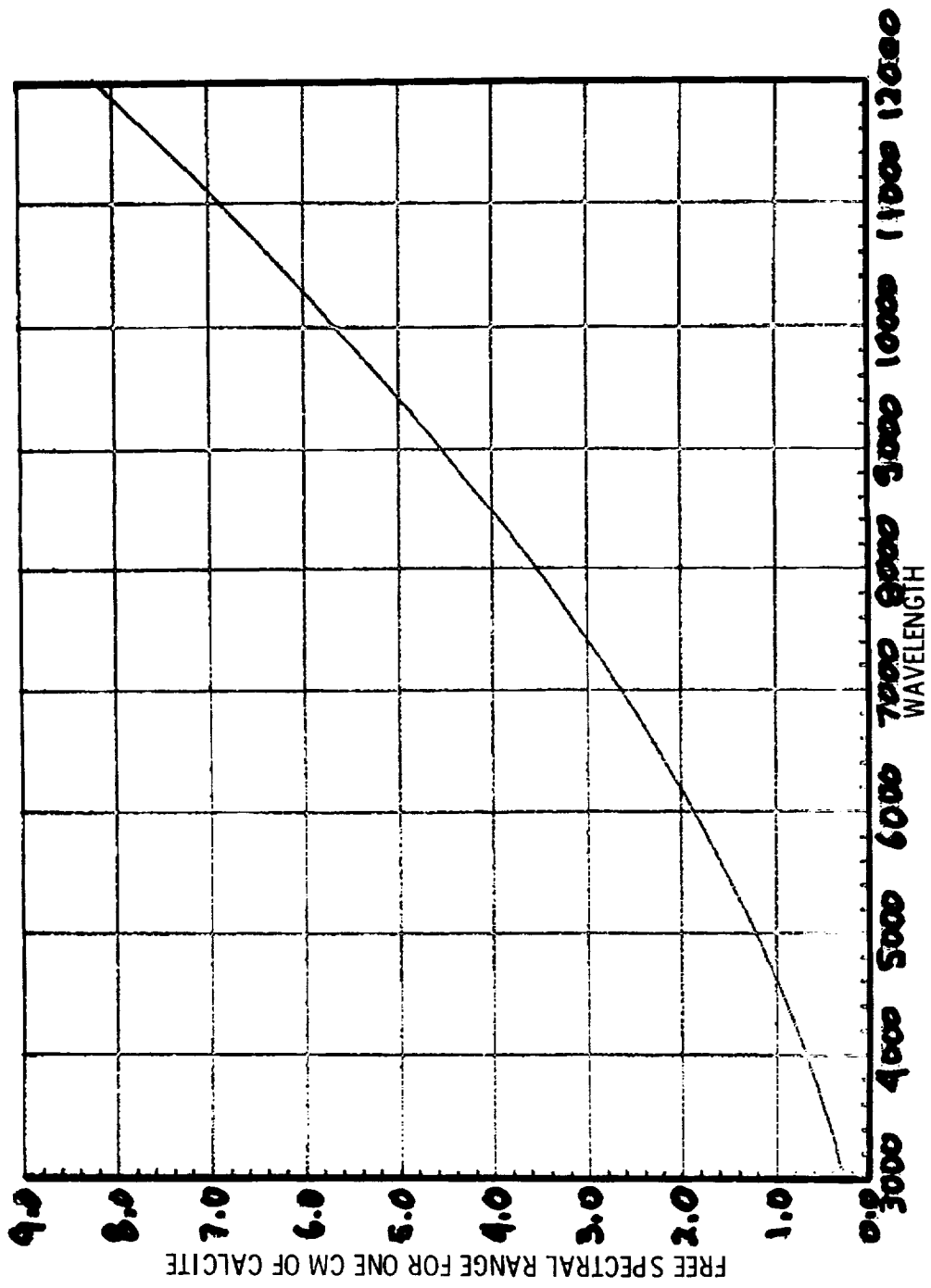


Figure 16