NASA CONTRACTOR REPORT

NASA CR-703

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DEVELOPMENT OF AN ALL DIELECTRIC INFRARED BEAMSPLITTER OPERATING IN THE 5 TO 30 MICRON REGION

by P. L. Heinrich, R. C. Bastien, A. Dos Santos, and M. Ostrelich

Prepared by
PERKIN-ELMER CORPORATION
Norwalk, Conn.
for Goddard Space Flight Center

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SUMMARY

This report describes the effort performed by the Perkin-Elmer Corporation for NASA-Goddard Space Flight Center under Contract Number NAS5-9560. Objectives of the program were the design, development and fabrication of three (3) infrared beamsplitter assemblies exhibiting optical and mechanical characteristics suitable for use in an interferometer spectrometer carried in a NIMBUS B satellite.

An all-dielectric infrared beamsplitter operating in the spectral region from 5 to 30 microns was successfully fabricated and delivered. A multilayer system of thin films deposited on a potassium bromide substrate was chosen to satisfy the requirements of the contract.

A promising extension of the above work that would yield a considerable increase in system performance is a program for the development of an unsupported (substrateless) beamsplitter system. Such a system could extend operational range to at least 50 microns and eliminate the need for path-length compensating elements, with subsequent reduction in weight.

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SECTION I

INTRODUCTION

1.1 SCOPE AND PURPOSE OF REPORT

This final report is concerned with documenting the results of an eleven-month program, sponsored by NASA-Goddard Space Flight Center, directed toward the design, development and fabrication of three infrared beamsplitter assemblies.

1.2 OBJECTIVE OF THE CONTRACT

The objective of the contract was to design, develop and fabricate three beamsplitter assemblies which exhibited optical characteristics suitable for use in an infrared interferometer spectrometer (IRIS). Additionally, since IRIS is intended for use in the NIMBUS B satellite, the beamsplitter components had to possess mechanical characteristics adequate to withstand weathering and launching into earth orbit.

The basic requirements called for a beamsplitter system (consisting of beamsplitting material, a substrate for the material, and a compensating plate) to be installed in a suitable mount. Briefly, the beamsplitter assembly was required to be designed and fabricated so as to:

(1) Survive a spacecraft launch and maintain optical properties during an extended mission in a spacecraft environment.

(2) Operate within a wavelength region of 5 to 30 microns with a capability of optical alignment using visible light.

1.3 TASK BREAKDOWN

Perkin-Elmer's general approach to the problem was to select suitable substrate and filming materials, design and experiment with beamsplitting and protective film systems, perform optical and mechanical tests, and analyze results to establish a working design. To accomplish these tasks in an orderly and controllable manner, the program effort was organized into three phases, as follows:

(I) Phase I was concerned with the selection of suitable substrate and filming materials for use as components of a beamsplitter system operating between 5 and 30 microns. Computed filter designs were experimentally tested for mechanical as well as optical properties. Results were analyzed and the best system was selected for fabrication of a prototype.

(II) Phase II was concerned with the fabrication of a prototype beamsplitter and compensating element. After fabrication, elements were tested for optical performance and mechanical stability.

(III) Phase III was concerned with the design, fabrication and testing of prototype and production beamsplitter mounts. Mounted beamsplitters were tested for their survival ability and performance characteristics. Components were redesigned as required and three mounted beamsplitters were fabricated and delivered to NASA-Goddard.

1.4 ORGANIZATION OF REPORT

Important characteristics of the final beamsplitter design are summarized in the following paragraph. A comprehensive discussion of each phase of the program effort outlined above is presented in Sections II, III and IV. Conclusions and Recommendations are stated in Section V and New Technology developments in Section VI.

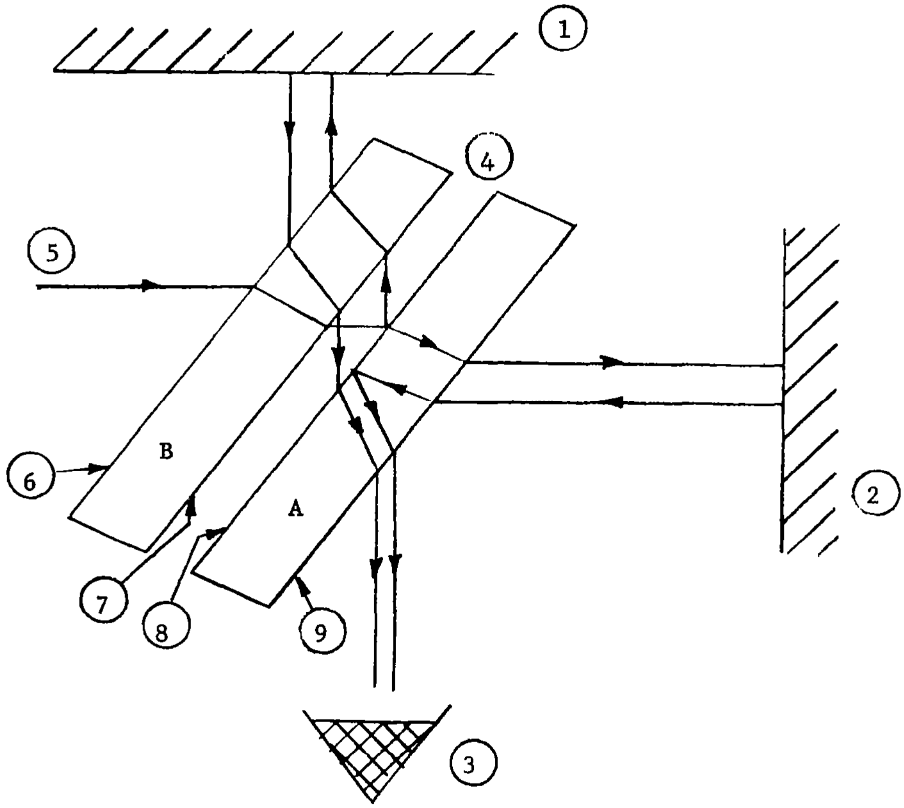
1.5 FINAL BEAMSPLITTER DESIGN CHARACTERISTICS

The beamsplitter assembly developed under the program reported herein consists of a beamsplitter system installed in a rigid mount.

The beamsplitter system, shown schematically in Figure 1 as part of an interferometer, is comprised of a substrate (A) which is coated with a series of beamsplitting and protective films, and a compensator plate (B) which is coated with a protective film. Element B is called a compensator plate because it equalizes the optical path in each leg of the interferometer.

Elements A and B are potassium bromide crystals selected for their homogeneity and high infrared transmission. Both elements are polished to better than one-tenth of a wavelength at 5 microns.

Element A is coated on one side with a protective film (KBr is highly soluble in water) and on the second side with a beamsplitter system of thin films. A small area of this beamsplitter surface (cross-hatched portion, Figure 2) is designed to operate in the visible region of the spectrum and is used as a reference surface to align the mounted beamsplitter. The remainder of the surface carries the infrared beamsplitter coating, yielding very nearly equal reflectance and transmission from 5 to 30 microns with negligible absorption.



A	Beamsplitter substrate
B	Compensator plate
1 & 2	Mirrors - highly reflecting from 5μ to 30μ.
3	Detector
4	25μ air gap
5	Incident radiation
6	Protective film coating
7	Protective film coating
8	Beamsplitter and protective film coatings
9	Protective film coating

Figure 1. Schematic of Beamsplitter System As Used In An Interferometer

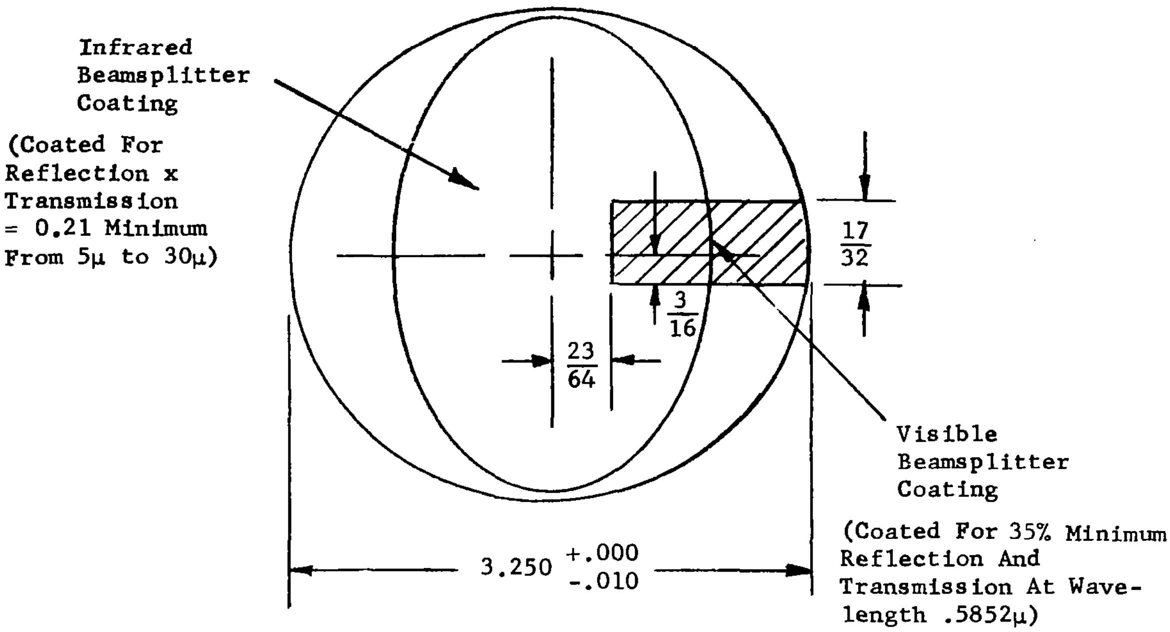


Figure 2. Beamsplitter Coatings

A photograph of the final beamsplitter assembly is shown in Figure 3. This system survived all tests necessary to insure confidence of satisfying orbital performance requirements. A transmission-reflection (RxT) curve typical of the final beamsplitter design is shown in Figure 4. Typical transmission curves of beamsplitter and protective coatings on KBr substrates are shown in Figures 5 through 9; a transmission curve obtained on an alternate substrate of CaF_2 is shown in Figure 9A. (It should be noted that energy not transmitted is reflected, as indicated in Figure 10, page 2-25.) Individual transmission curves for the delivered beamsplitter assemblies are shown in Figures 25 through 27, pages 4-18 through 4-20.

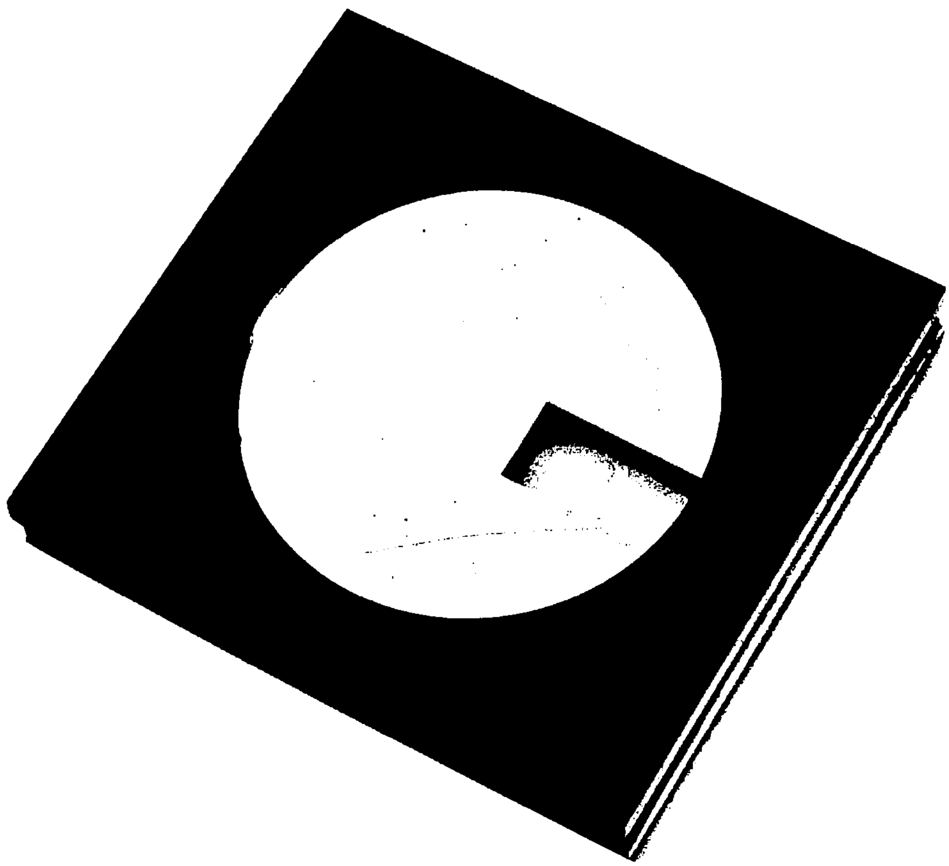


Figure 3. Final Beamsplitter Assembly

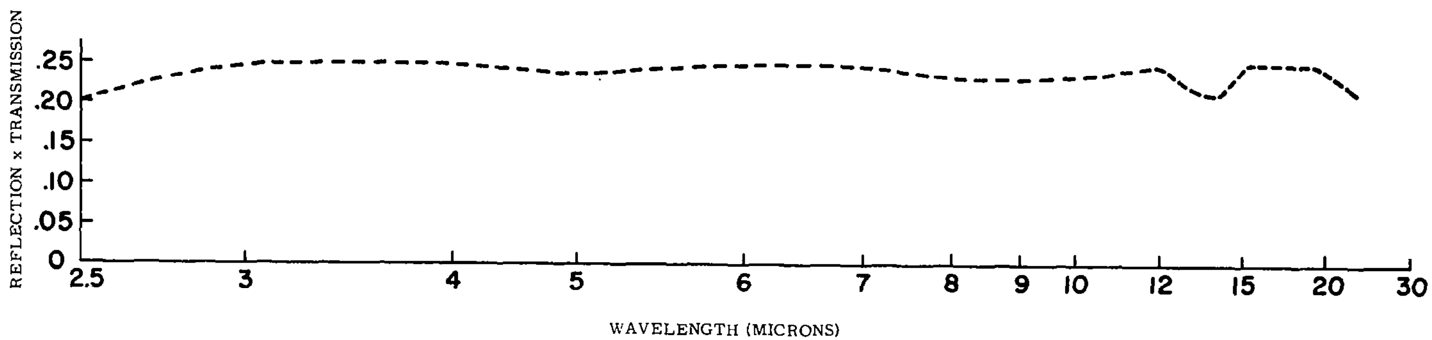


Figure 4. Reflection x Transmission Curve for Infrared Beamsplitter

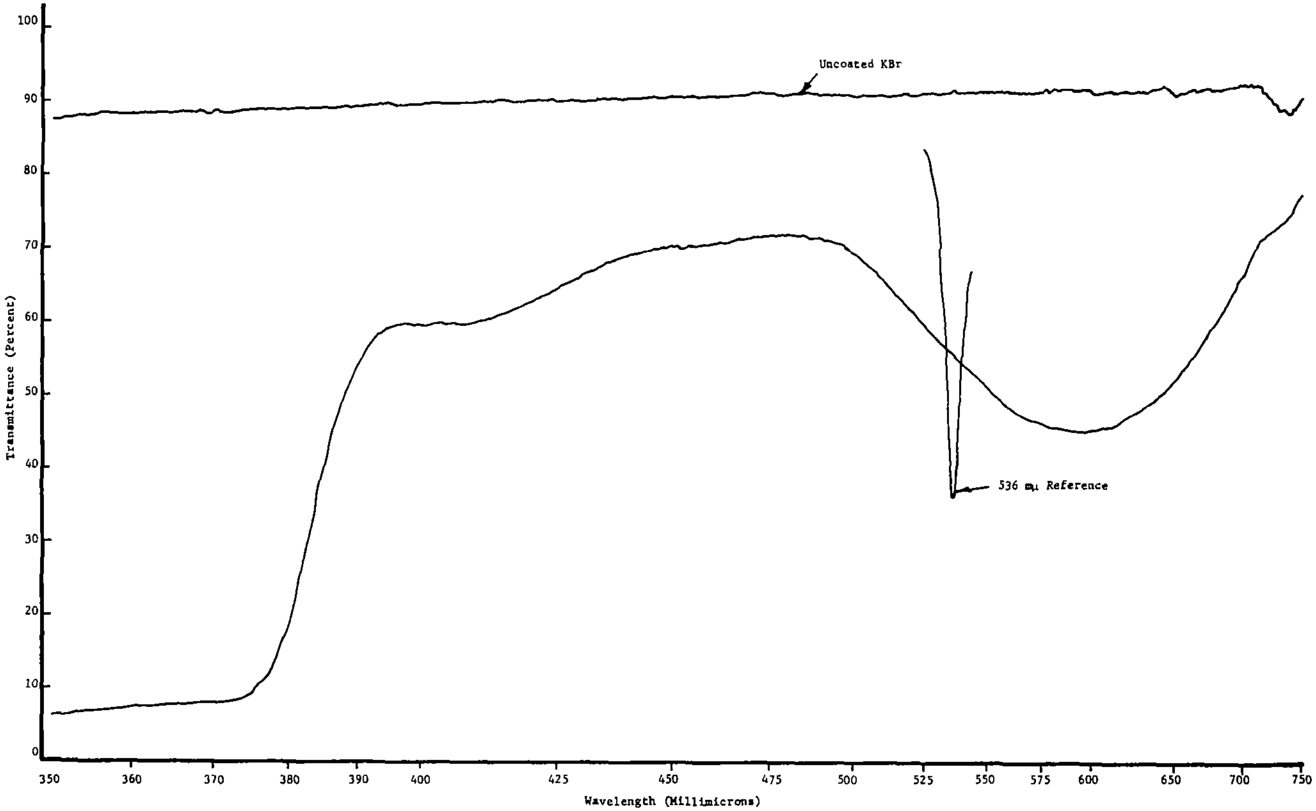


Figure 5. Visible Beamsplitter Coating on KBr substrate. Range 350mμ to 750mμ (Normal Incidience, Uncoated KBr Used as Reference.

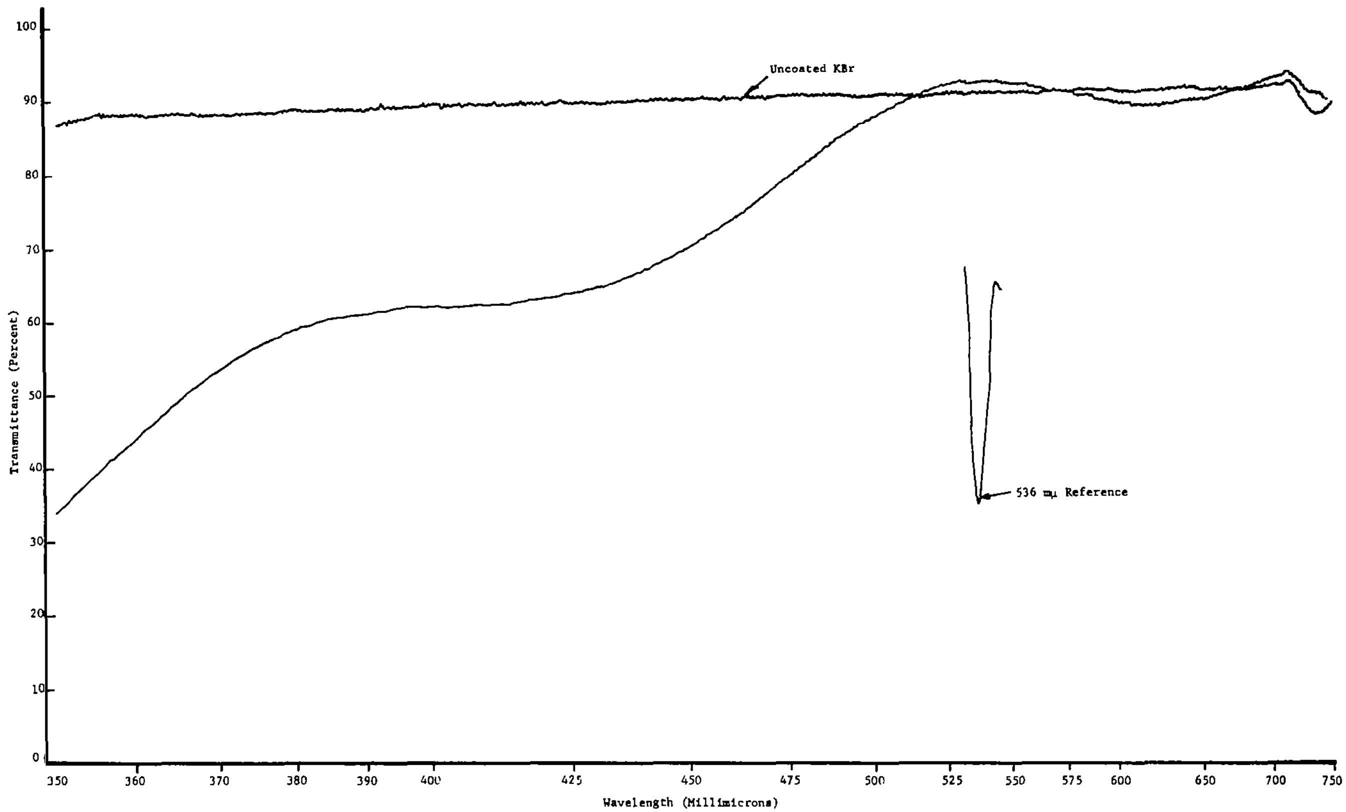


Figure 6. Protective Coating on KBr Substrate. Range 350mμ to 750mμ (Normal Incidence. Uncoated KBr Used as Reverence.)

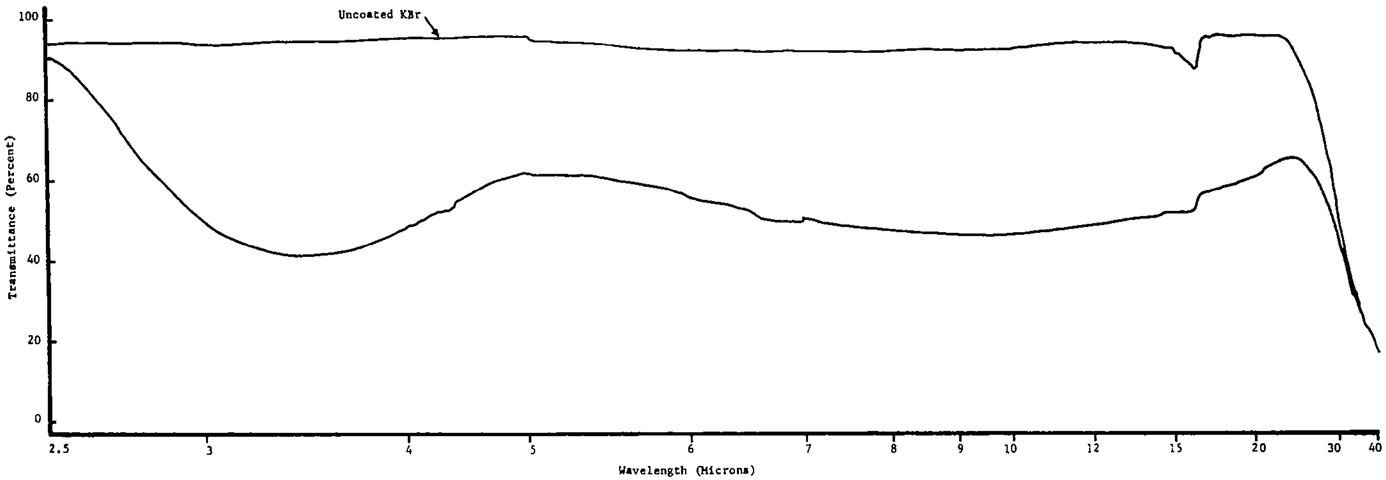


Figure 7. IR Beamsplitter Coating on KBr Substrate. Range 2.5μ to 40μ (Normal Incidence. Uncoated KBr Used as Reference.)

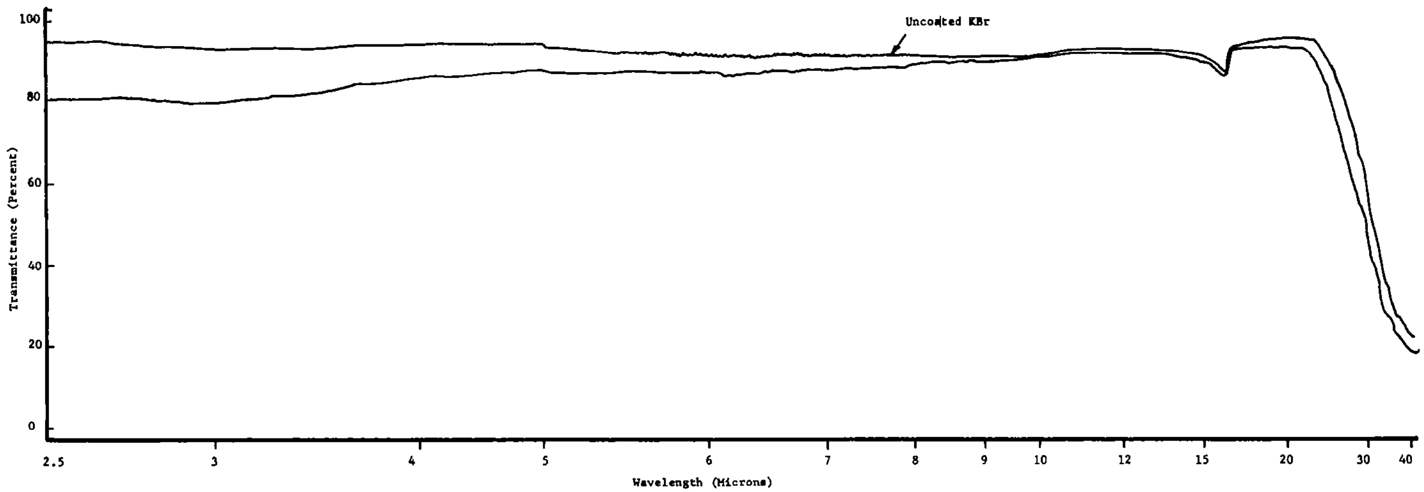


Figure 8. Protective Coating on KBr substrate. Range 2.5μ to 40μ
(Normal Incidence. Uncoated KBr Used as Reference.)

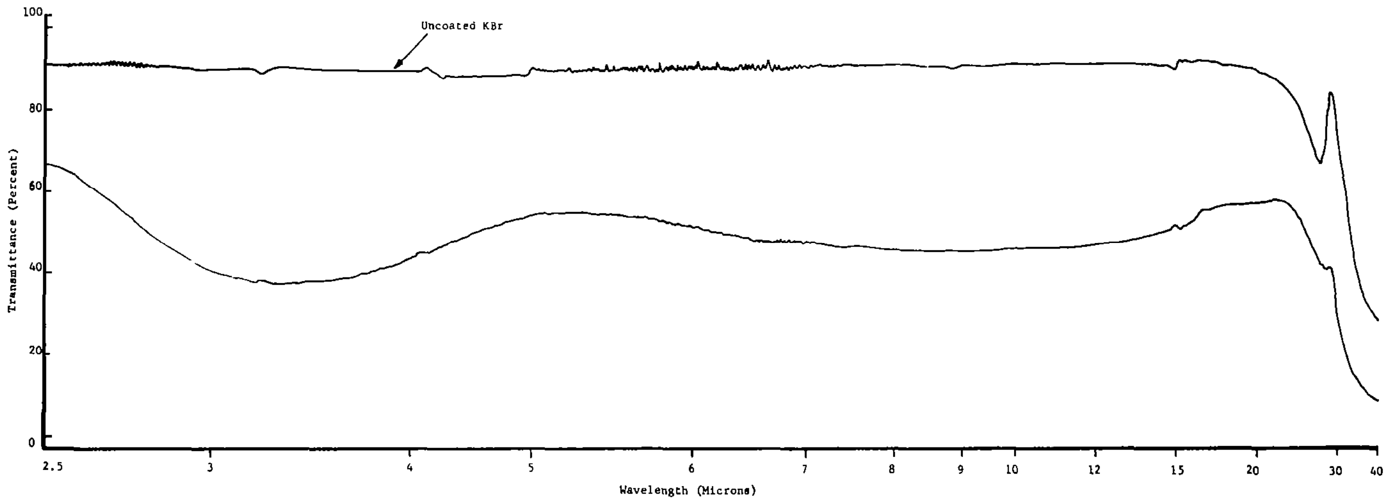


Figure 9. IR Beamsplitter and Protective Coatings on KBr Substrate. Range 2.5μ to 40μ. (Normal Incidence. Uncoated KBr Used as Reference.)

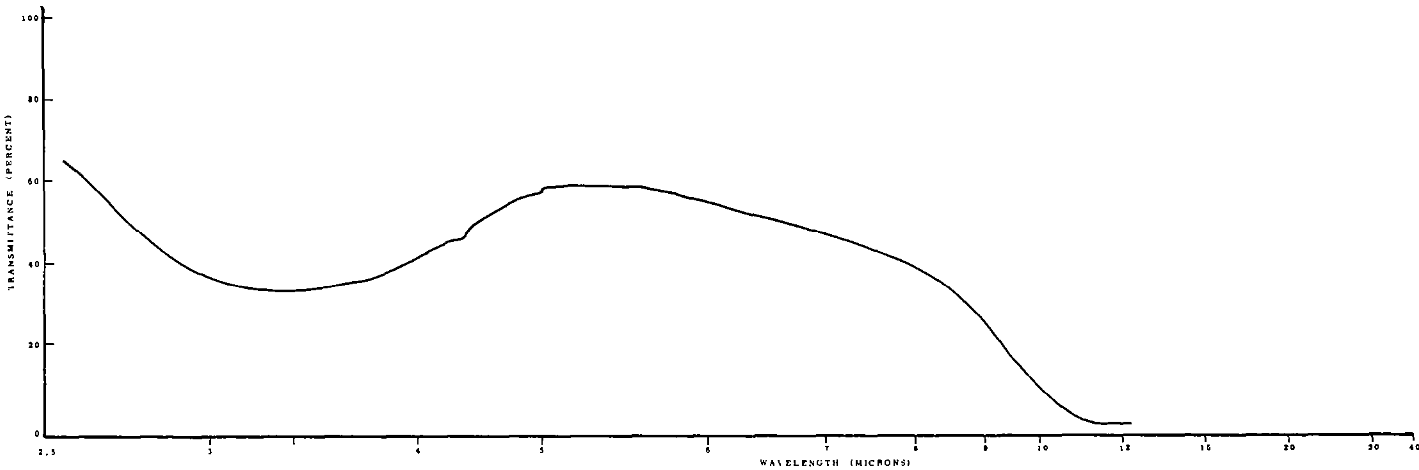


Figure 9A. Transmission Characteristics of IR Beamsplitter and Protective Coatings on CaF_2 Substrate.

SECTION II

DISCUSSION OF PHASE I EFFORT

2.1 SUMMARY OF PHASE I EFFORT

Phase I was concerned with the selection of suitable substrate and coating materials for use as components of a beamsplitter system operating between 5 and 30 microns.

Five substrates were selected for study: potassium bromide (KBR), cesium iodide (CsI), thallium bromide (TlBr), calcium fluoride (CaF_2) and Irtran-3. Material homogeneity and optical transmission measurements were made. Surface flatness tests were performed before and after temperature cyclying. The experiments yielded KBr as the most promising material for operation between 5 and 30 microns; and CaF_2 as useful for narrow-band applications.

Coating materials were studied for optical and mechanical properties. Results from over 500 individual experiments and tests led to the selection of useful filming materials.

Potential beamsplitter film designs were computed and curves predicting optical performance in the 5 to 30μ range obtained. Experiments were performed and a comparison made between predicted and actual performance. The film system which best satisfied all optical and mechanical requirements was a 13 layer design. This system was selected for fabrication of a prototype beamsplitter.

2.2 SELECTION OF SUBSTRATE MATERIAL

2.2.1 Selection Considerations

Many substrate materials were considered as beamsplitter elements for the infrared interferometer spectrometer. Due to serious alignment problems all materials opaque to visible light were dropped from consideration. Thus, such durable materials as germanium, silicon and cadmium telluride could not be used. The most promising infrared transmitting elements remaining were the alkali halides, rare earth salts and the irtrans. Several factors were considered in choosing prospective substrate materials. An ideal substrate material would have the following properties:

(a) High visual transmittance.

(b) Negligible absorption from 5μ to 30μ.

(c) Freedom from strain, i.e., homogeneity such that optical retardation through the substrate is $< \lambda/2$ at 500 $m\mu$.

(d) Insoluble in water.

(e) Ability to resist induced strain and surface flatness deformation due to vacuum heating and cooling cycling.

(f) Rigidity and mechanical stability.

(g) Ability to retain alignment and flatness qualities after rigorous shock and vibration tests simulating rocket liftoff into space.

Needless to say, no such material was known. Thus, the logical approach was first to rule out all materials that had absolutely no chance of meeting the requirements and then to select from the remaining materials the most promising. Preliminary investigations narrowed the search to the following materials: Potassium Bromide (KBr), Cesium Iodide (CsI), Thallium Bromide (TlBr), Calcium Fluoride (CaF_2), and Irtran-3.

2.2.2 Procedure

Raw substrate material samples were inspected thoroughly upon receipt. All elements were first checked for diameter and thickness and then for strain with a polariscope to determine whether or not the material was of interferometer quality. Each sample was then vacuum baked to 150°C to determine whether strain was relieved, induced or modified. A minimum of eight samples of each material were examined. Only TlBr failed this test.

Each element then was hand polished by standard techniques to the optical flatness described in the test data sheets below. The polished blanks were then photographed in an interferometer arrangement to record surface figure. They were then heat cycled to 150°C in vacuum and again photographed to determine whether or not each material had held its figure. TlBr as well as CsI failed this test, which simulated test conditions encountered during the vacuum coating cycle. Moreover, additional tests also revealed that the same two materials changed optical figure merely when allowed to sit overnight under standard temperature and pressure conditions. Although these two materials proved to be unstable interferometer elements they are potentially good window materials to very long wavelengths in the infrared. Due to this fact several attempts were made to coat each one with a multilayer protective optical coating; successful results were obtainted on TlBr only.

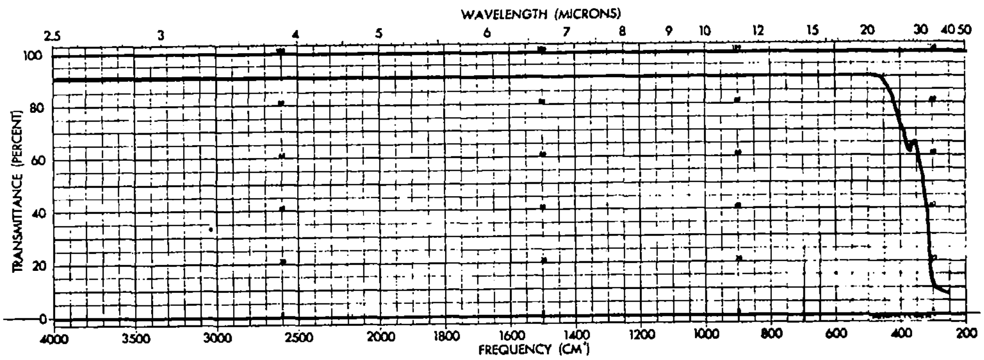
2.2.3 Summary of Test Results

As was noted previously, preliminary investigations revealed KBr, CsI, TlBr, CaF_2, and Irtran-3 to be the most promising substrate materials. After intensive investigation of each material all but KBr and CaF_2 were eliminated as potential infrared beamsplitter substrates suitable for vacuum coating and capable of maintaining performance after launching into space. KBr was found to satisfy the requirement for a substrate material capable of operating throughout the spectral region of interest, viz., 5 to 30 microns; CaF_2 proved suitable for narrow-band applications. Test data sheets on these elements are provided below. All tests for strain and optical flatness were performed on samples at least 0.3 inches thick and 3.0 inches in diameter.)

POTASSIUM BROMIDE (KBr)

Potassium bromide represents a compromise material in that it has neither the best optical properties of the materials studied nor the best mechanical properties. However, its optical and mechanical properties are completely adequate to meet all of the beamsplitter requirements. Although KBr has absorption free transmittance only to 21μ compared to 40μ for CsI it is rigid enough so that if dropped it will shatter rather than bend in lead-like fashion as does CsI. KBr also is relatively strain free.

The high solubility of KBr makes it extremely difficult to coat and to protect against humidity. Nevertheless, beamsplitter film coatings were successfully deposited on KBr and withstood repeated "breath tests"; some even withstood submersion in water for a few minutes without major deterioration.

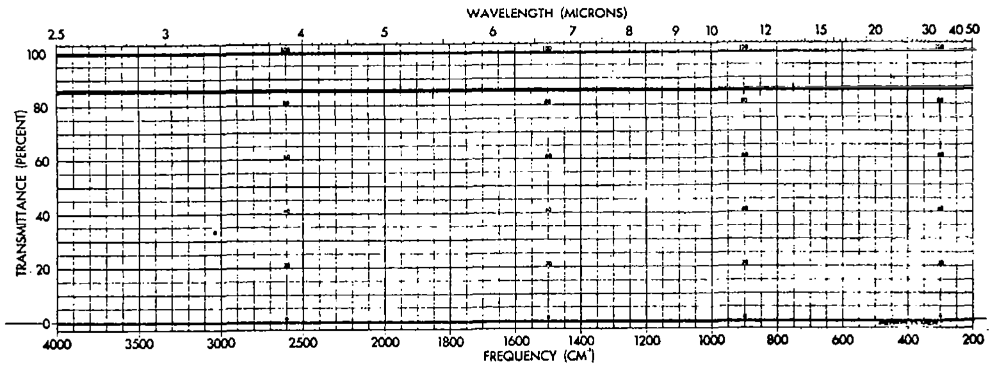


TRANSMISSION OF KBr

TRANSMISSION:	Optimum to 22μ; 50% at 30μ; zero at 40μ.
REFRACTIVE INDEX:	1.53 at 5.0μ
STRAIN:	3-1/4" diameter elements that were 3/8" thick exhibited some edge strain but none within a 2-7/8" clear aperture
OPTICAL FLATNESS BEFORE HEAT CYCLING:	$R_1 = 2\lambda$ concave; $R_2 = 2\lambda$ concave
OPTICAL FLATNESS AFTER HEAT CYCLING:	$R_1 = 2\lambda$ concave; $R_2 = 2\lambda$ concave
SOLUBILITY:	53.48 gm/100 gm water at 0°C.
SUPPLIER:	Harshaw Chemical Co.
COMMENTS:	No effects were observed after vacuum heat cycling. Polishing to required figure of λ/2 (on reflection) requires considerable skill when diameter to thickness ratio exceeds 10 to 1.

CESIUM IODIDE (CsI)

Of the materials investigated CsI evidenced by far the most desirable optical properties. However, CsI exhibited mechanical properties that were quite poor. Polishing to the required figure was extremely difficult and when flatness was obtained the surface figure did not remain stable. Furthermore, many attempts were made to vacuum deposit beamsplitting and protective coatings on the highly soluble CsI, but all coatings failed the "breath test".

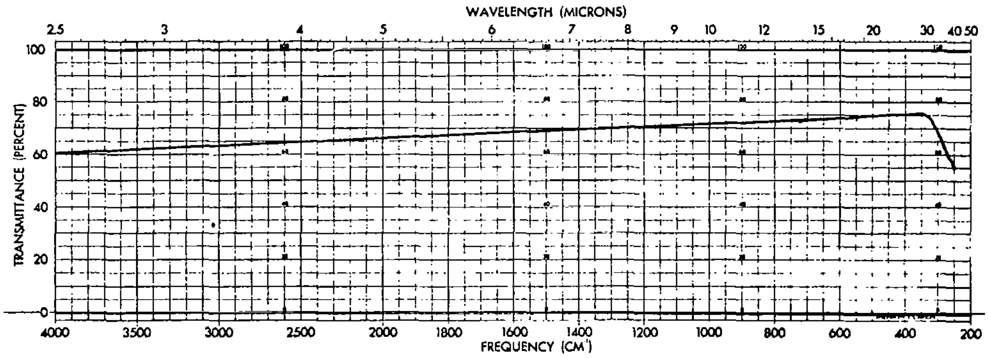


TRANSMISSION OF CsI

TRANSMISSION:	Optimum to 70μ
REFRACTIVE INDEX:	1.74 at 5.0μ
STRAIN:	Relatively strain free.
OPTICAL FLATNESS BEFORE HEAT CYCLING:	R_1 = 3λ convex; R_2 = 3λ convex
OPTICAL FLATNESS AFTER HEAT CYCLING:	R_1 = 5λ convex; R_2 = 5λ convex
SOLUBILITY:	44 gm/100gm water at 0°C.
SUPPLIER:	Harshaw Chemical Co.
COMMENTS:	CsI samples 0.3" thick x 3.0" diameter would not maintain λ/2 optical flatness.

THALLIUM BROMIDE (TlBr)

Thallium Bromide was found to be virtually absorption free to 30μ and had no peculiar absorption bands in the region of interest. In addition, TlBr was extremely easy to coat and protect with vacuum evaporated films. Unfortunately, TlBr turned out to be unusuable as an infrared beamsplitter substrate for the following two reasons. Of eight substrate samples examined every one exhibited multiple strain patterns with abrupt optical path retardation equivalent to approximately 600mμ per cm, whereas 20 mμ is the minimum requirement for homogeniety. Secondly, both strain patterns and optical figure varied greatly and unpredictably when subjected to vacuum heat cycling. All attempts at annealing TlBr to relieve strain proved fruitless.

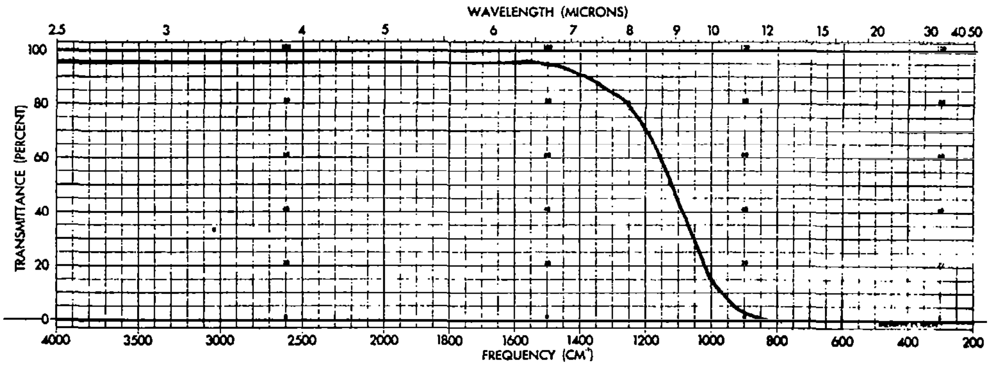


TRANSMISSION OF TlBr

TRANSMISSION:	Optimum to 29μ; 55% at 40μ
REFRACTIVE INDEX:	2.15 at 5.0μ
STRAIN:	Very large amount of strain present. Heat cycling, polishing and edge polishing failed to remove strain.
OPTICAL FLATNESS BEFORE HEAT CYCLING:	R_1 = 5λ convex; R_2 = 3λ concave
OPTICAL FLATNESS AFTER HEAT CYCLING:	R_1 = 100λ convex; R_2 = completely distorted
SOLUBILITY:	0.15 gm/100 gm water at 25°C.
SUPPLIER:	Harshaw Chemical Co.
COMMENTS:	Cleavage lines were observed in substrate before baking cycle and increased during the cycle. Half of samples tested exhibited cleavage lines.

CALCIUM FLUORIDE (CaF_2)

Calcium Fluoride was investigated for use in a beamsplitter operating between 3.3μ and 7.4μ. Although of no use beyond this range it was, nevertheless, very attractive because of its mechanical and optical properties in the spectral region of interest. CaF_2 was quite durable and supported optical films excellently. It was rather difficult to polish, but, due to its low solubility, no difficulty was experienced in coating over fine sleeks on its surface.

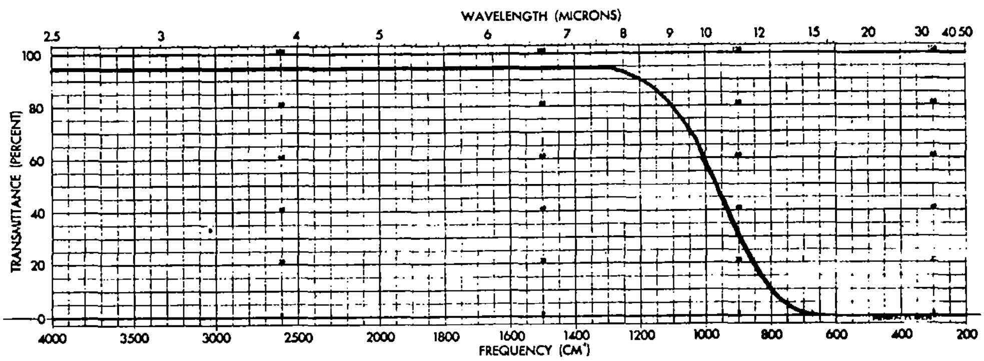


TRANSMISSION OF CaF_2

TRANSMISSION:	Optimum to 6.8μ; 50% at 8.8μ; zero at 12μ
REFRACTIVE INDEX:	1.399 at 5.0μ
STRAIN:	No strain, but some cleavage lines along edge of substrate.
OPTICAL FLATNESS BEFORE HEAT CYCLING:	R_1 = 1/2λ convex; R_2 = 1λ concave
OPTICAL FLATNESS AFTER HEAT CYCLING:	R_1 = 1/2λ convex; R_2 = 1λ concave
SOLUBILITY:	0.0017 gm/100 gm water at 26°C.
SUPPLIER:	Harshaw Chemical Co.
COMMENTS:	Very good mechanical properties, but limited transmission properties.

IRTRAN-3 (Hot Pressed CaF_2)

Irtran-3 was studied for use in a beamsplitter operating from 3.3μ to 7.4μ. Its similarity to single crystal CaF_2 suggested its possible use as an alternate to CaF_2 in the event that material failed vibration and shock testing. All tests on this material were performed on 1 inch diameter, 1/8 inch thick samples due to the fact that 3-1/4 inch diameter samples cost twelve times as much as the same size sample of single crystal CaF_2. Test results showed that Irtran-3 could not be supplied without pinholes and that it was impossible to polish to a smooth surface due to the polycrystalline nature of the material. All attempts at coating or protecting Irtran-3 were without success. Many pinholes were observed after each coating due to the random rod-like structure of the substrate. Microscopic examination of samples revealed pinhole type defects throughout the material. These defects made it less desirable than CaF_2.



TRANSMISSION OF

TRANSMISSION:	Optimum to 7.8μ; 50% at 10.2μ; zero at 14.3μ
REFRACTIVE INDEX:	1.399 at 5.0μ
SUPPLIER:	Eastman Kodak Co.
COMMENTS:	Due to high cost and poor preliminary results on the 1 inch diameter Irtran-3 samples 3 inch diameter substrates were not purchased. Consequently no polishing, heat cycling or strain experiments were performed.

2.3 DESIGN OF BEAMSPLITTER FILM SYSTEM

2.3.1 Design Considerations

The basic beamsplitter requirement was that it transmit (T) and reflect (R) nearly equal amounts of energy at wavelengths between 5μ and 30μ. Oscillations were to be kept to a minimum both in amplitude and quantity. The efficiency of the system, defined at the product RxT, was required to be at least 0.21 in the region of interest. (Ideal performance exists when RxT = 0.25).

These requirements, and others specified previously, put several restraints on potential filming materials. Some considerations that governed the selection of suitable beamsplitter films were:

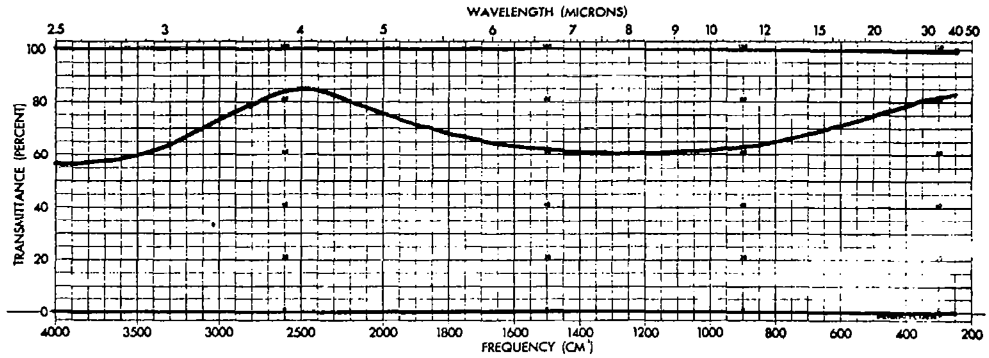
(a) Materials must be free of significant absorption in the thicknesses required by the beamsplitter design.

(b) The evaporated films must be relatively free of stress and pinholes in order to survive temperature-humidity cycling.

(c) The final film design must have low solubility in water to inhibit deterioration by prolonged exposure to humid atmosphere.

(d) The filming materials used must have proper refractive index to meet the design requirements.

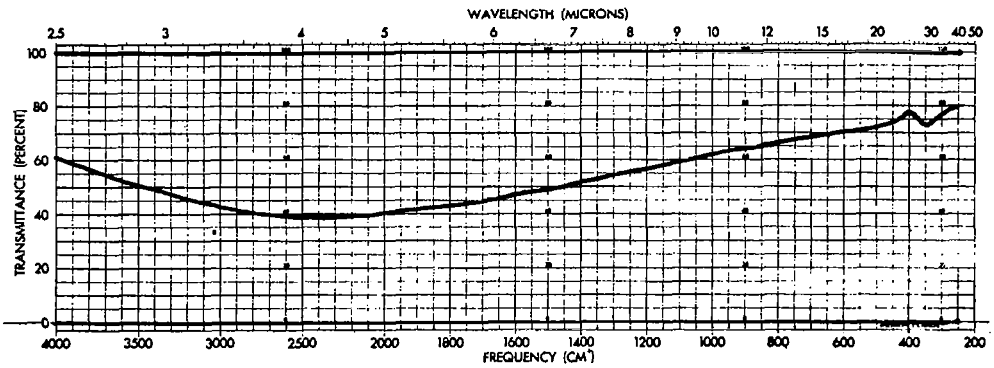
CADMIUM TELLURIDE (CdTe)



THE TRANSMISSION OF CdTe

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 8.0μ
REFRACTIVE INDEX:	2.59 at 8.0μ
SOLUBILITY:	Insoluble in water
TRANSMISSION:	Optimum to 40μ
ABSORPTION BANDS:	None
COMMENTS:	Cadmium telluride has excellent optical properties, but crazed when used in combination with germanium films. At 4μ the film of CdTe is just λ/2 optical thickness. Transmission of 85% at this wavelength is the same as uncoated CsI.

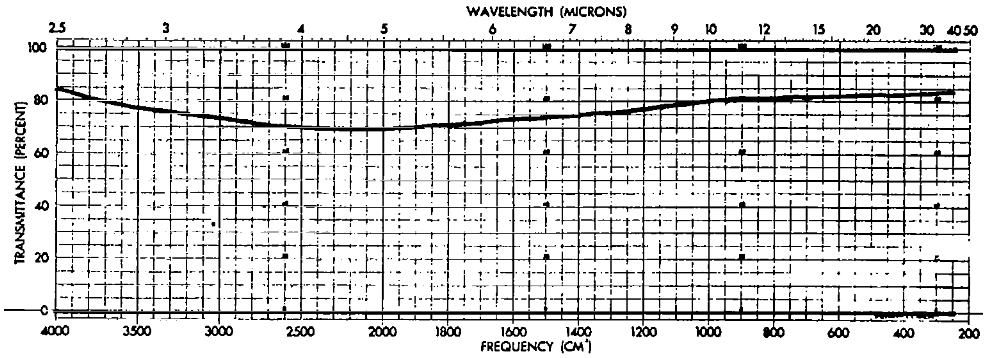
GERMANIUM (Ge)



THE TRANSMISSION OF Ge

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 4.2μ
REFRACTIVE INDEX:	3.7 at 4.2μ
SOLUBILITY:	Insoluble in water
TRANSMISSION:	Optimum to 26μ
ABSORPTION BANDS:	5% at 29μ (very slight absorption 14 to 29μ)
COMMENTS:	Germanium was the only filming material available with a high enough refractive index to fulfill our beamsplitter requirements. Although tellurium has a higher refractive index it is inferior to germanium both mechanically and optically. Germanium was chosen as the final film of our beamsplitter stack design. It was the only film that adequately protected the film stack from deterioration in a simple "breath test".

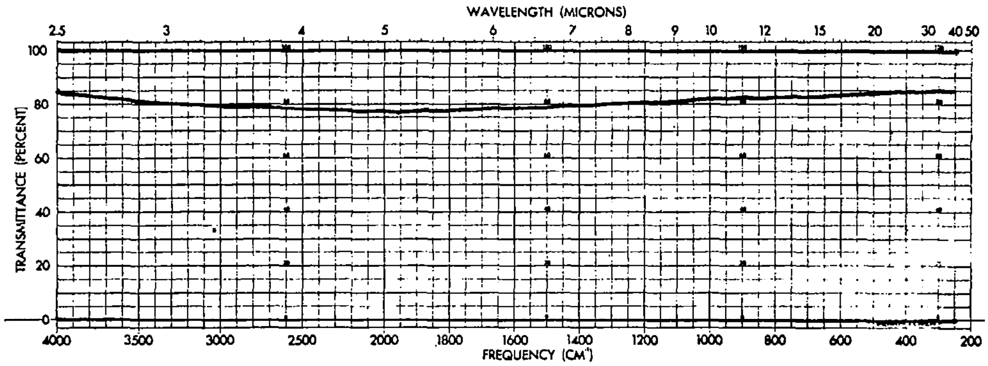
THALLIUM IODIDE (TlI)



THE TRANSMISSION OF TlI

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 4.5μ
REFRACTIVE INDEX:	2.3 at 4.5μ
SOLUBILITY:	Insoluble in water
TRANSMISSION:	Optimum to 40μ
ABSORPTION BANDS:	None
COMMENTS:	Thallium Iodide has excellent optical properties to beyond 40μ. It is insoluble and has an intermediate refractive index. The material is soft and has rather poor mechanical properties as a single film and in a film stack. This material was not acceptable for the beamsplitter or protective film requirements.

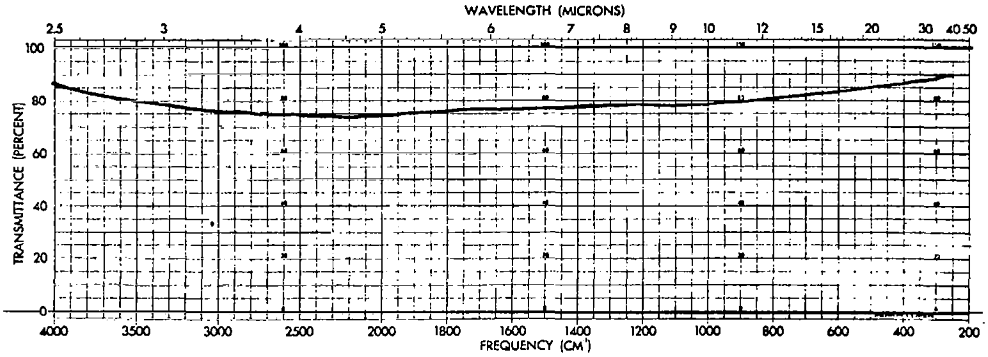
THALLIUM CHLORIDE (TlCl)



THE TRANSMISSION OF TlCl

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 4.5μ
REFRACTIVE INDEX:	2.06 at 4.5μ
SOLUBILITY:	0.32 gm/100gm water at 20°C
TRANSMISSION:	Optimum to 40μ
ABSORPTION BANDS:	None
COMMENTS:	Thallium chloride has excellent transmission properties beyond 40μ. It is a very low stress material and flows after evaporation virtually eliminating stress. Thus it acts as a buffer in the middle of the beamsplitter film system. Its high solubility has not been a deterrent. Some of our successful beamsplitter designs have included TlCl as one of the films.

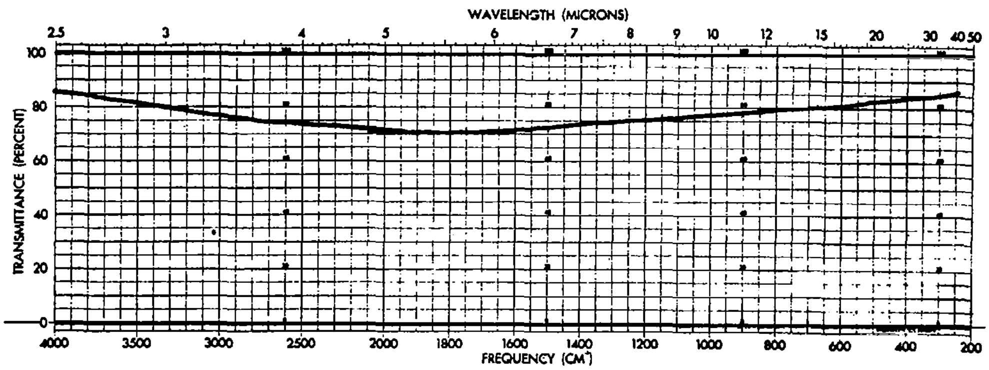
THALLIUM BROMIDE (TlBr)



THE TRANSMISSION OF TlBr

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 5μ
REFRACTIVE INDEX:	2.15 at 5μ
SOLUBILITY:	0.05gm/100gm water at 25°C
TRANSMISSION:	Optimum to 40μ
ABSORPTION BANDS:	None
COMMENTS:	Thallium bromide has a useful refractive index. It is low in solubility and stress. TlBr was one of the filming materials used in the successful beamsplitter system. It was one of the key materials used in combination with PbF_2 and Ge that produced the desired Herpin equivalent index films.

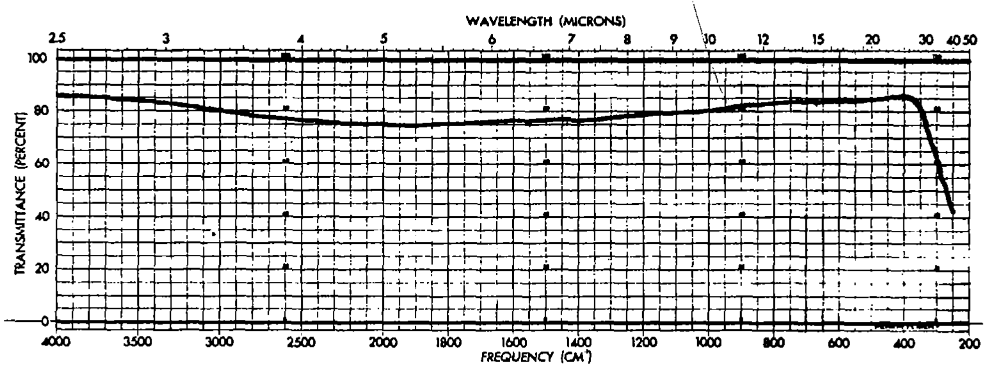
KRS-5 ($TlBr-TlI$)



THE TRANSMISSION OF KRS-5

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 5μ
REFRACTIVE INDEX:	2.25 at 5μ
SOLUBILITY:	0.05 gm/100gm water at 20°C
TRANSMISSION:	Optimum to 40μ
ABSORPTION BANDS:	None
COMMENTS:	Evaporated KRS-5 exhibits properties intermediate between TlBr and TlI. It has a median refractive index and develops better film properties than either component alone. Films of KRS-5 and germanium were deposited which met the beamsplitter optical and mechanical requirements.

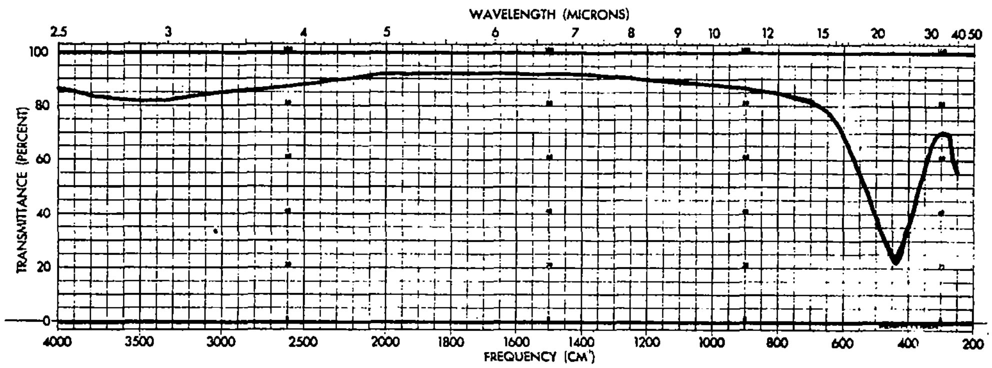
ZINC SULFIDE (ZnS)



THE TRANSMISSION OF ZnS

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 5μ
REFRACTIVE INDEX:	2.15 at 5μ
TRANSMISSION:	Optimum to 22μ; 50% at 35μ; zero at 40μ
ABSORPTION BANDS:	None
COMMENTS:	Thick films of zinc sulfide have excellent properties to 22μ. The absorption of the above film is about 6 at 30μ. ZnS is incompatible with other filming materials on BKr and CsI substrates for the beamsplitter requirement. However, some success was realized with ZnS film combinations as a protective film system for the compensator elements.

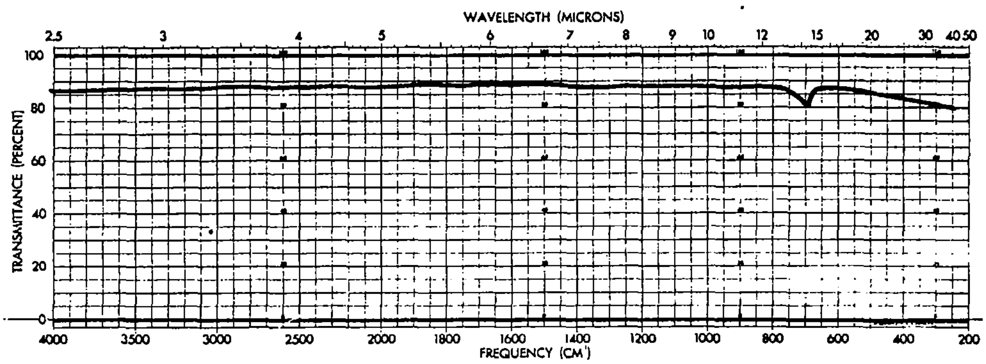
MAGNESIUM FLUORIDE (MgF_2)



THE TRANSMISSION OF MgF_2

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 6μ
REFRACTIVE INDEX:	1.32 at 6μ
SOLUBILITY:	0.0076gm/100gm water at 18°C
TRANSMISSION:	Optimum to 12μ; 50% at 20μ; zero at 40μ
ABSORPTION BANDS:	3% at 2.9μ (water); 80% at 22μ to 26μ
COMMENTS:	Thick films of MgF_2 have fair to poor mechanical properties. The above film is useless as a beamsplitter film above 12μ. MgF_2 and $ThOF_2$ exhibit water band absorption in the 2.7μ to 3.4μ and 6.1μ range. This effect in MgF_2 is about 15% of that in $ThOF_2$.

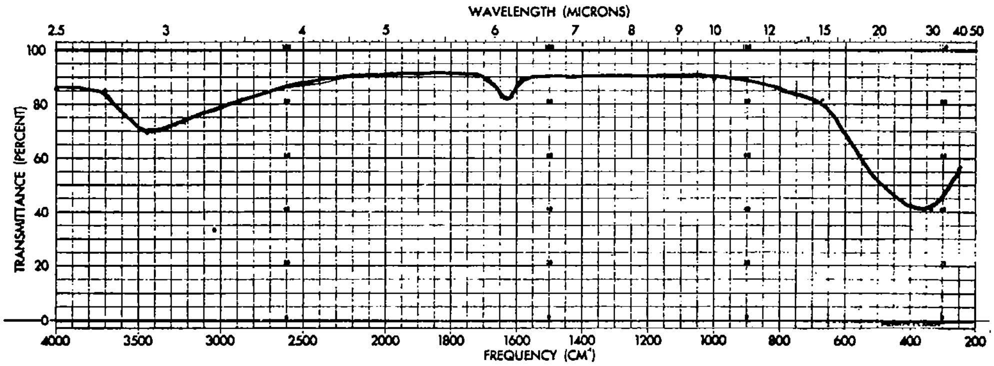
LEAD FLUORIDE (PbF_2)



THE TRANSMISSION OF PbF_2

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 6μ
REFRACTIVE INDEX:	1.66 at 6μ
SOLUBILITY:	0.05gm/100gm water at 25°C
TRANSMISSION:	Optimum to 13μ; zero at 40μ
ABSORPTION BANDS:	6% at 14.5μ
COMMENTS:	Lead Fluoride is an excellent starting film between substrate and beamsplitter stack. Its low solubility seems to react favorably at the substrate interface making it possible to apply additional films which together resist peeling, cracking and humidity. Attempts are being made to utilize this material's mechanical properties in thinner films in order to avoid performance loss in the 14.5μ region due to absorption.

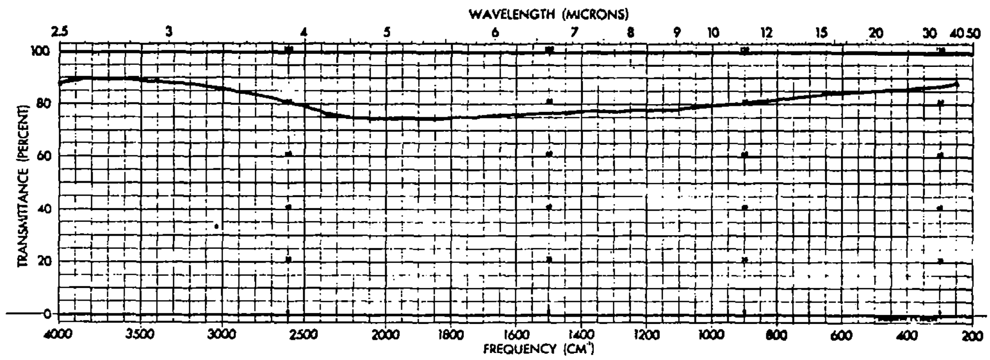
THORIUM OXYFLUORIDE ($ThOF_2$)



THE TRANSMISSION OF $ThOF_2$

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 6μ
REFRACTIVE INDEX:	1.5 at 6μ
TRANSMISSION:	Optimum to 11μ; 50% at 24μ
ABSORPTION BANDS:	18% at 2.7μ to 3.3μ; 7% at 6.1μ (both water bands) 50% at 27μ
COMMENTS:	Thorium oxyfluoride is very nearly insoluble in water. Two relatively deep water bands occur at 2.9μ and 6.1μ. Indications are that these are caused by absorbed water of crystallization when the film is exposed to the atmosphere. $ThOF_2$ films QWOT at .6μ are useful as components of a protective film system for KBr substrates.

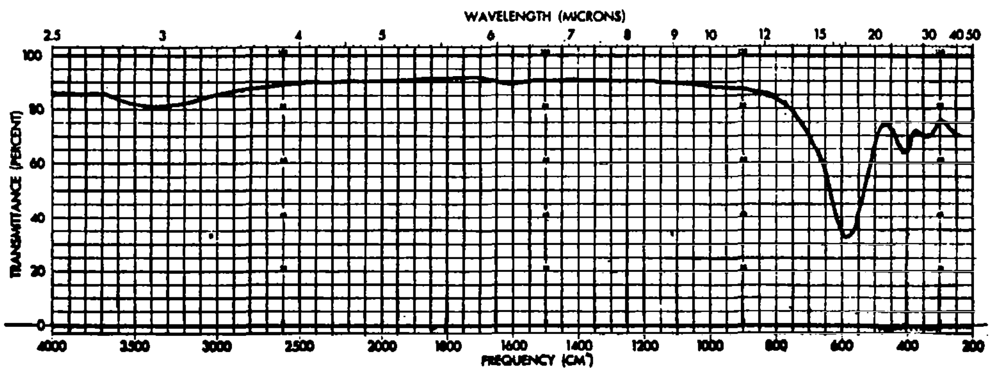
KRS-6 (TlBr-TlCl)



THE TRANSMISSION OF KRS-6

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 5μ
REFRACTIVE INDEX:	2.1 at 5μ
SOLUBILITY:	0.32gm/100gm water at 20°C
TRANSMISSION:	Optimum to 40μ
ABSORPTION BANDS:	None
COMMENTS:	KRS-6 exhibits mechanical properties between those of its constituents TlBr and TlCl. Best results toward developing a visible beamsplitter coating on KBr at 6000Å have been with KRS-6 - PbF_2 multilayers.

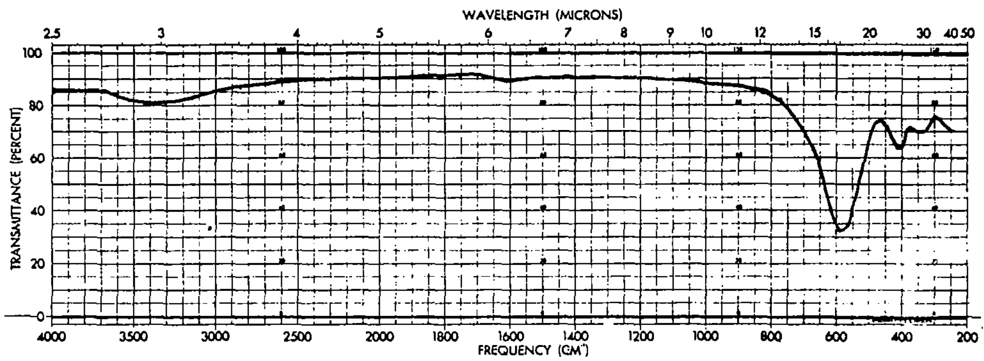
CRYOLITE (Na_3AlF_6)



THE TRANSMISSION OF CRYOLITE

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 5.5μ
REFRACTIVE INDEX:	1.24 at 10μ
TRANSMISSION:	Optimum to 12μ; 50% at 16μ
ABSORPTION BANDS:	Slight water bands at 2.9μ and 6.1μ Deep band at 17.5μ
COMMENTS:	Cryolite is not acceptable as a filming material for the IR beamsplitter or protective films.

CHIOLITE ($5NaF.3AlF_3$)



THE TRANSMISSION OF CHIOLITE

SUBSTRATE:	CsI
FILM THICKNESS:	QWOT at 5.5μ
REFRACTIVE INDEX:	1.24 at 5.5μ
TRANSMISSION:	Optimum at 12μ; 50% at 16μ; zero at 40μ
ABSORPTION BANDS:	Slight water bands at 2.9μ and 6.1μ Deep absorption band at 16.5μ
COMMENTS:	Chiolite is virtually identical to cryolite. Its major absorption band is centered at a slighly shorter wavelength. Its water bands are quite similar to those observed in cryolite and MgF_2.

2.3.2 Design Approach

2.3.2.1 Theoretical Development

Polished surfaces of various materials transmit less energy than the incident radiant energy. The energy not transmitted appears in the reflected beam, assuming no absorption losses. The reflected energy is higher for materials having higher indices of refraction and is nearly constant over a wide wavelength range.

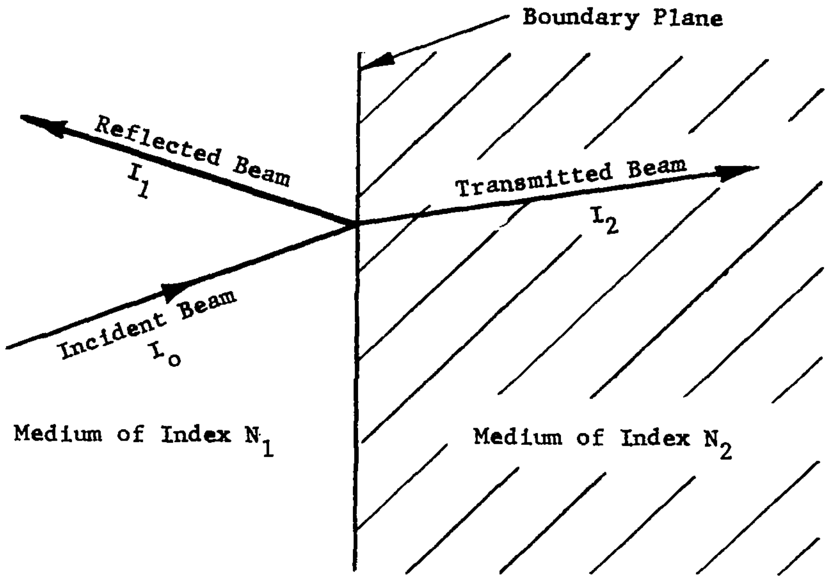
Figure 10 shows such a surface and gives the Fresnel formula for calculating reflectance ratio using the indices of refraction as parameters. If medium 1 is air, then $N_1 = 1$. If medium 2 is some high index material, index 5, for example, then $N_2 = 5$ and $R = 0.44$. Such a surface is a relatively good beamsplitter.

Further, a beamsplitter system with reasonably uniform reflectance and transmittance properties over a wide wavelength range may be realized if:

a. The high-index medium in Figure 10 is regarded as a high-index film, one side of which is matched to a substrate with a multilayer film system designed to suppress reflectivity to as near zero as possible at the substrate-high index boundary. The other side of the high-index film is understood to be against air. (See Figure 11.)

b. The index of the film satisfies the familar Fresnel reflectance formula,

$$\sqrt{R} = \left| \frac{1 - N_{p+1}}{1 + N_{p+1}} \right| \tag{1}$$



I_o = Incident Energy

I_1 = Reflected Energy

I_2 = Transmitted Energy

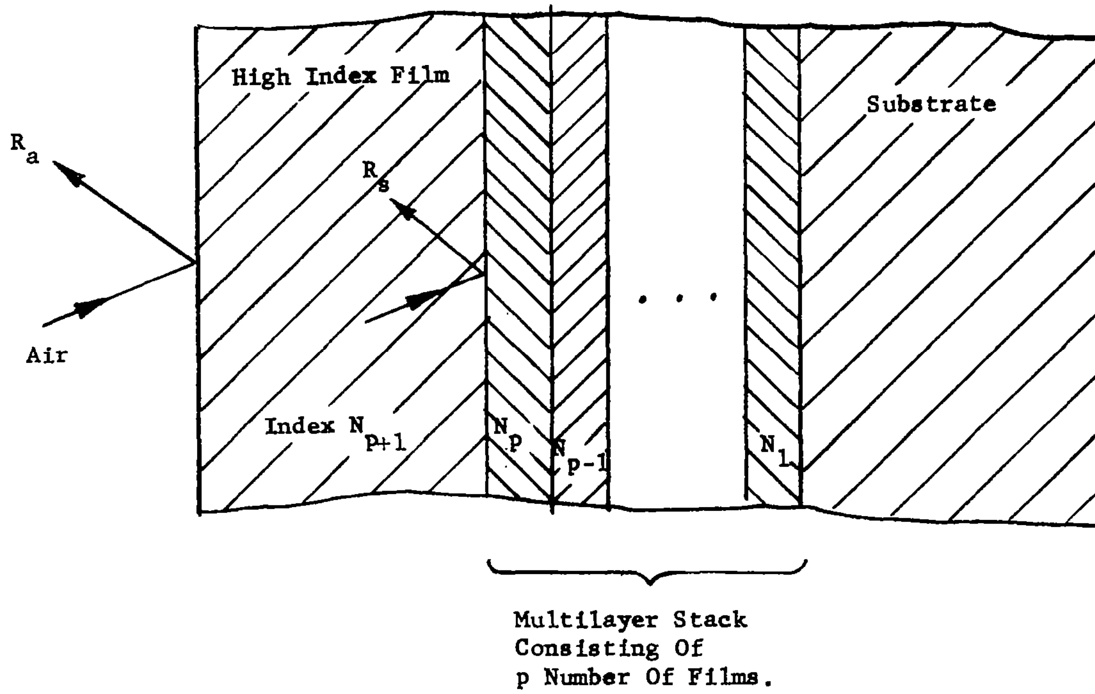
R = Energy Reflectance Ratio

T = Energy Transmittance Ratio

$$R = \frac{I_1}{I_o} = \left(\frac{1 - N_2/N_1}{1 + N_2/N_1}\right)^2$$

$$T = \frac{I_2}{I_o} = 1\text{-}R$$

Figure 10. Illustration of Reflection and Transmission at a Polished Surface



R_a = Reflectance at the air/high-index film boundary

R_s = Reflectance of the high-index film/multilayer stack boundary

Figure 11. Matching of High-Index Film to Low-Index Substrate with Multilayer Film System

Since the most desirable reflectance is R = 0.50, this requires N_{p+1} to be 5.83. A material of such high index is not available. The nearest index to this value is that of Tellurium namely 5.1. However, experimentation proved this material unacceptable for our application. The most suitable high index film was germanium with an index of 4.0. This was the material actually used so all further discussions will use index 4.0.

In order to realize the broad band reflection characteristics possible with a single high index-air boundary it was necessary to suppress virtually all of the reflection from the high index film-substrate boundary. A film system was designed which did just that. Film systems of this type have been discussed by Jacobson[1] where a single inhomogeneous film is used and by Berning,[2] where the indices of the different films are related by a linear equation. An analytic expression for such a system is difficult to attain and perhaps impossible with elementary functions. However, if the film indices are related exponentially, a compact expression can be found

$$N_k = N_o \left(\frac{N_{p+1}}{N_o}\right)^{k/p+1} \qquad (2)$$

Where N_{p+1} and N_o are the indices of the high-index film and substrate respectively. N_k is the index of the k^{th} film in the matching film system consisting of p films.

Then, an expression for the energy reflectance (R_s) at the high index-multilayer-substrate junction is:

$$\sqrt{\frac{R_s}{1-R_s}} = \sinh \alpha \cdot \frac{\sin (p+1) \gamma}{\sin \gamma} \qquad (3)$$

where $\cos \gamma = \cosh \alpha \cdot \cos \theta$

and $\alpha = \frac{1}{2(P+1)} \cdot \log_e \left(\frac{N_{p+1}}{N_o} \right)$

(θ is the phase thickness of a single film and each film has the same phase thickness.)

2.3.2.2 Computer Study

Computer investigations of reflectance vs. wavelength from 5μ to 30μ were made for some exponentially stepped film systems. Figure 12 shows calculated reflectances for systems composed of 1, 3, and 9 films respectively. The values are for 45° incidence angle and represent the average reflectance, i.e.,

$$R_{av} = \frac{1}{2} (R_{\parallel} + R_{\perp})$$

where $R_{\parallel}$ is reflectance of energy polarized in the plane of incidence

and

$R_{\perp}$ is reflectance of energy polarized normal to the plane of incidence.

It is evident from the curves that the tendency is towards flatter response as the number of films is increased. It is also seen that as the number of films becomes large, the limiting value of $R_{av} = 0.35$ is approached. This is the expected average reflectance for a single high index film of index 4 against air where the incident energy is at 45° to the normal in air. It is worth noting that only odd numbers of films were considered. In the exponential step graded film system all the reflection amplitudes are equal and all films are a quarter wave optical thickness. An odd number of films produces an even number of boundaries and these reflection amplitudes then cancel one another in pairs. If an even number of films were used there would be one extra boundary

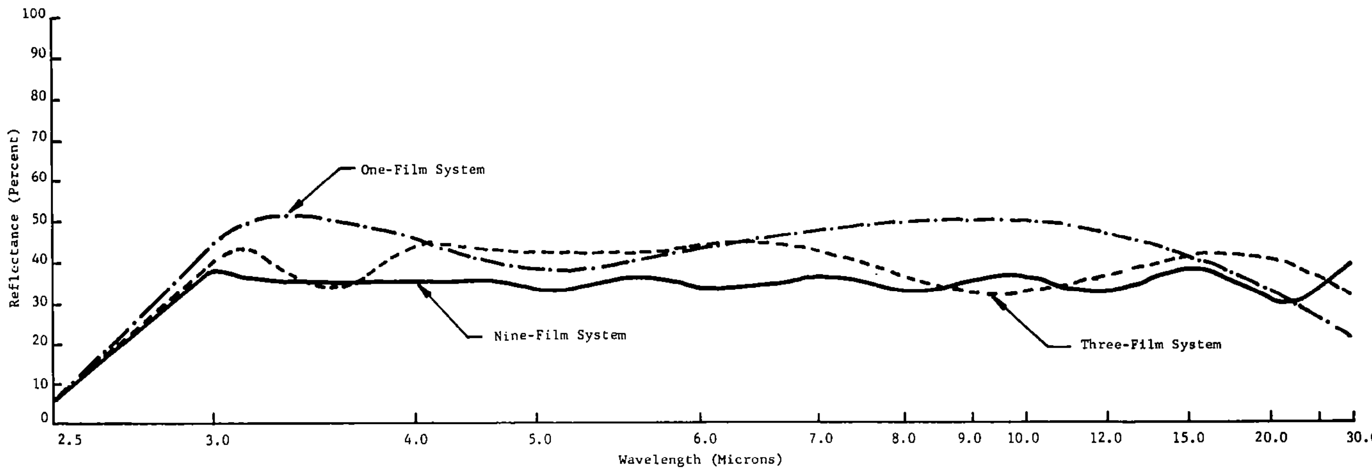


Figure 12. Computed Reflectance vs. Wavelength for 45° Incidence Angle in Air.

and it would reduce suppression of reflectivity and ultimately cause interference banding with the high index-air boundary.

In addition to computing reflectance vs. wavelength for several film designs, some experimental films were also fabricated. Computed vs. experimental curves for a one-film system are shown in Figure 13. Germanium was the high index film against air and KRS-5 was the matching film between Ge and the KBr substrate. Agreement between computed and experimental curves is excellent.

Figure 14 shows a computed three-film system and a thirteen-layer Herpin-equivalent-index film system. As shown in Figure 15, the required indices for a three-film system are 3.15, 2.47, and 1.94. Only KRS-5 satisfied an index requirement. The other two films were not available so we used the method of Epstein[3] and Berning[2] to design an equivalent film system having the required indices and optical thicknesses. The thirteen-layer system was designed as follows:

<u>Air</u>	<u>Stack A</u>	
1.0	H + (.166M, .166H, .332M, .166H, .166M) +	
	<u>Stack B</u>	<u>Substrate</u>
	K + (.166L, .166M, .332L, .166M, .1666L)	1.53

where H, M, K and L represent films of one quarter (90°) wave optical thickness at 5.0μ. The films and their indices are

H(Ge):	4.00
M(TℓBr):	2.15
K(KRS-5):	2.47
L(PbF_2):	1.70

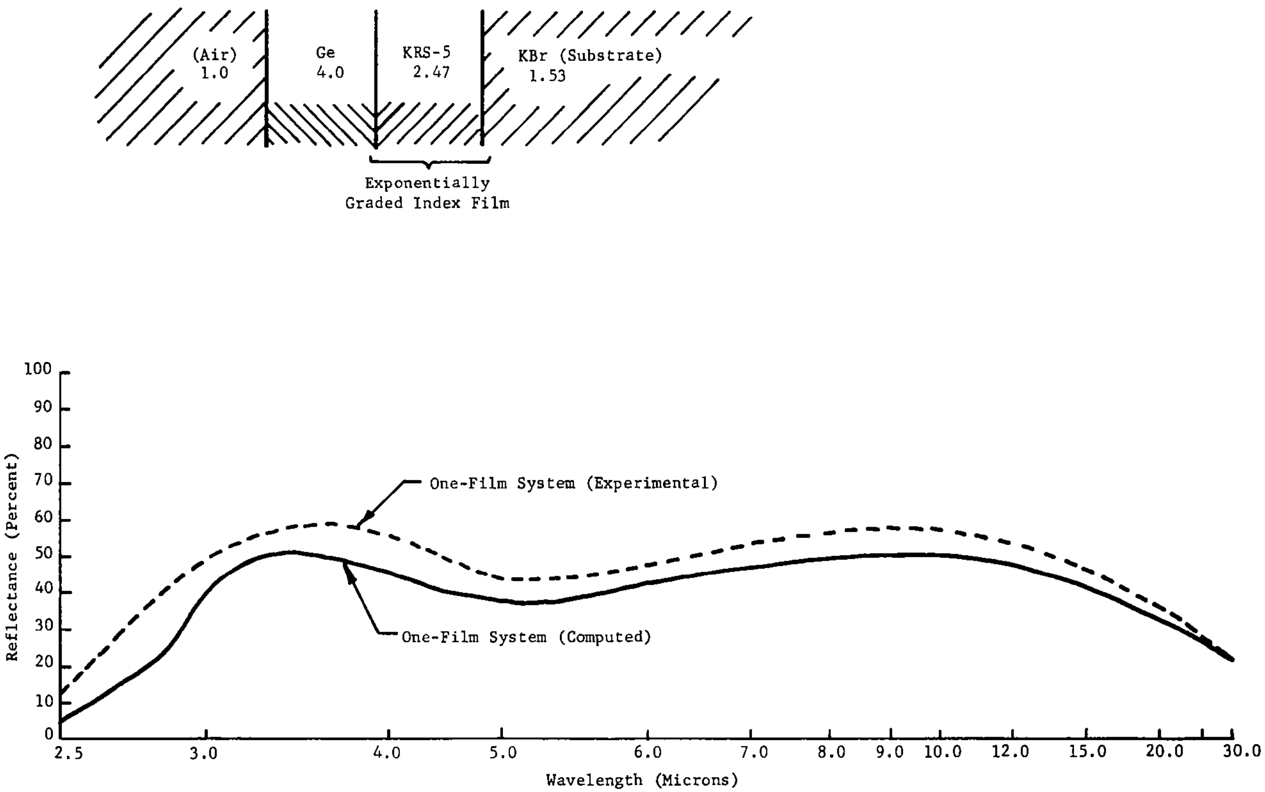


Figure 13. Computed and Experimental Curves of Reflectance vs. Wavelength for 45° Incidence Angle in Air.

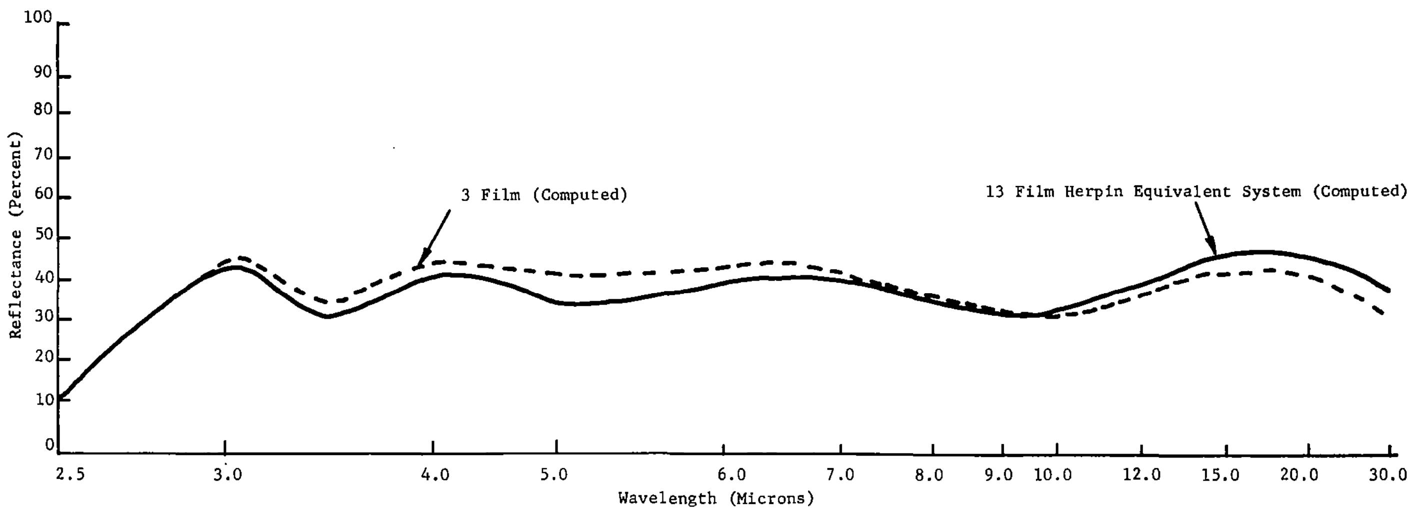


Figure 14. Computed Curves of Three-Film and Thirteen-Layer Film System.

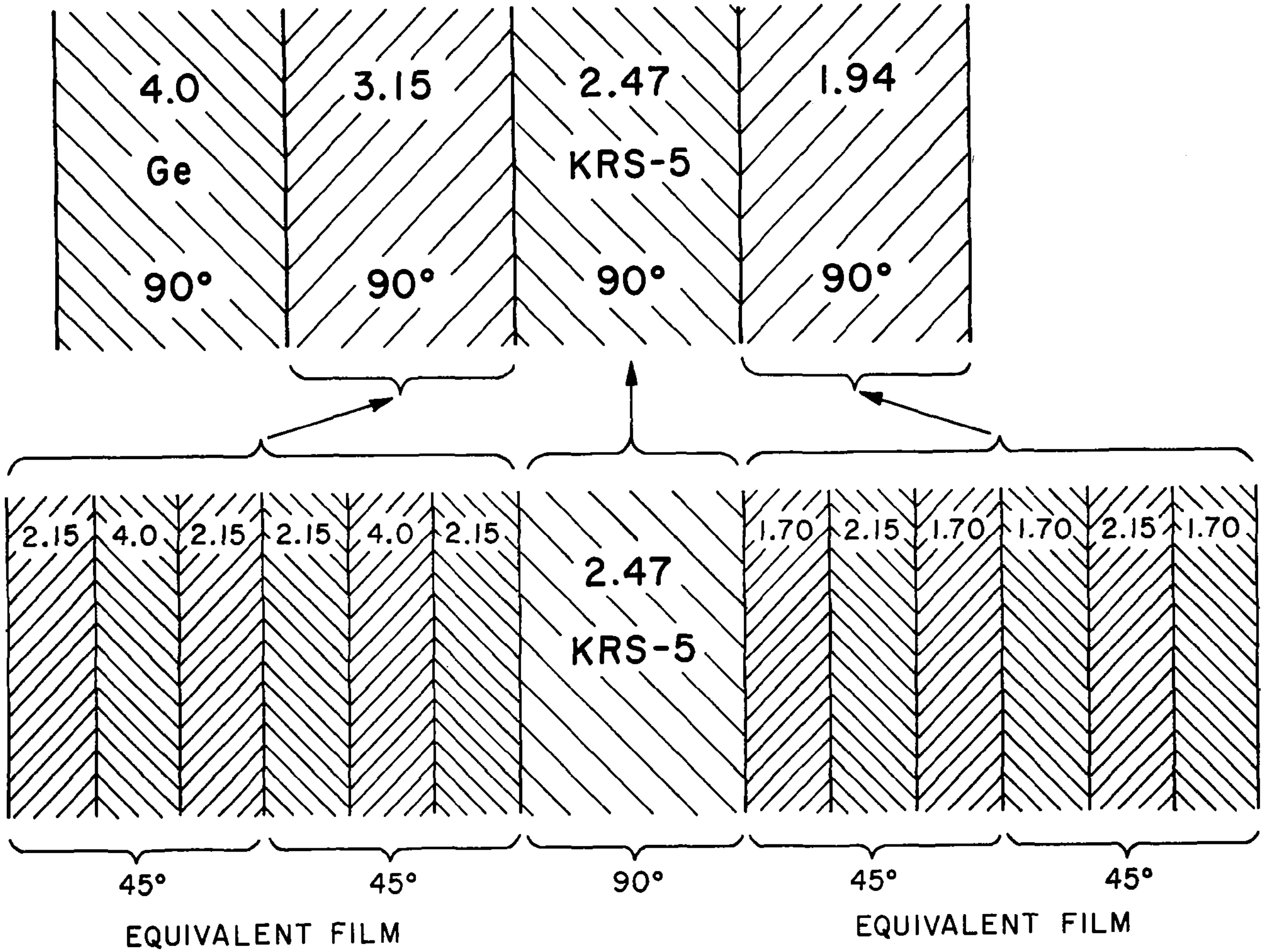


Figure 15. Construction of Multilayer Film Stack.

Stack (A) consists of two symmetrical periodic structures with equivalent index 3.50 and phase thickness 90°. Stack (B) consists of two symmetrical periodic structures with equivalent index 1.94 and phase thickness 90°. The design is illustrated in Figure .

Figure 16 shows computed vs. experimental curves for the 13-layer Herpin-equivalent index system. Agreement between computed and actual curves is extremely good.

Attempts at making equivalent index systems of more than thirteen films were unsuccessful and so this data is not presented here. It seems as though the limiting number of these films (on KBr substrates) is about 13 before the system becomes mechanically unstable.

2.3.2.3 Experimental Tests

Infrared beamsplitter coatings were deposited on KBr, CsI, TlBr, Irtran (3) and CaF2 substrates. The first line of testing was a simple "breath test" with photomicrographs taken before and after testing so that evaluations of deterioration could be made. Detailed records were maintained on every experiment performed in the form of photographs, technical details of experiments, and results.

The same film system generally performed in a different manner on each substrate. Optical properties were very similar since index of refraction differences were relatively small from one substrate to the next. However, wide variations were found in mechanical properties. Results are summarized in Table I below.

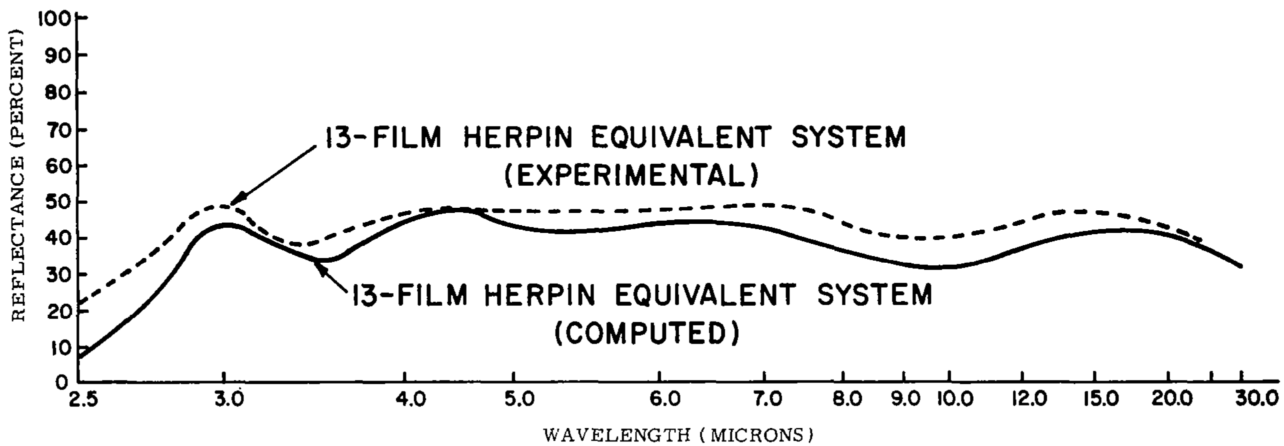


Figure 16. Computed vs. Experimental Herpin-Equivalent Film System

TABLE I

MECHANICAL PROPERTIES OF SELECTED
IR-BEAMSPLITTER COATINGS ON VARIOUS SUBSTRATES

Substrate Material	Substrate Temperature	Breath Test	70% ±3% Humidity @ 30°C, 24 hrs	Pinhole Defects	Remarks
Potassium Bromide	25°C	Passed	Passed	Very few	Good
Potassium Bromide	100°C	Failed	Failed	Few	Many stress line defects
Cesium Iodide	25°C	Failed	Failed	Few	Many stress line defects
Cesium Iodide	100°C	Failed	Failed	Many	Many stress line defects
Thallium Bromide	25°C	Passed	Passed	None	Excellent
Thallium Bromide	100°C	Failed	Failed	Many	Failed
Calcium Fluoride	25°C	Passed	Passed	Very few	Excellent
Calcium Fluoride	100°C	Passed	Passed	Very few	Excellent

The mechanical stability of the IR coatings on TlBr and CaF2 was excellent. Unfortunately, as reported earlier in the substrate selection discussion, TlBr was unacceptable due to excessive strain and CaF2 absorbed greatly above 8 microns. Beamsplitter coatings on KBr, CsI and Irtran-3 were poorer mechanically than on the first two materials. This seems to be due to the fact that the water solubility of KBr and CsI greatly exceeds the others. (Irtran-3 had numerous pinhole defects.) It was more difficult to obtain smooth surfaces on the more soluble materials.

2.3.3 Summary of Test Results

Potential coating materials were exhaustively tested to reveal optical and mechanical properties suitable for use as a system of beamsplitter films. Test results are summarized in test data sheets below.

Computed designs and experimental tests revealed a film system of Ge, TℓBr, KRS-5, and PbF_2 as giving the best all-around performance. The best mechanical properties for the film systems were realized when TℓBr and PbF_2 were used in the first layer. Finally, coatings deposited on heated substrates were found to be inferior to coatings deposited at room temperature.

2.4 SELECTION OF PROTECTIVE COATINGS

2.4.1 Coating Characteristics

As reported earlier, KBr was chosen for the compensator and beamsplitter substrates. Since this material is quite soluble in water and deteriorates rapidly when exposed to water vapor, a protective film was developed for the three exposed crystal surfaces. Criteria for selection of a protective coating were as follows:

a. High infrared transmission; preferably the films should be anti-reflecting in the range 5 to 30μ.

b. High visual transmission in the 0.6μ region so as not to hinder beamsplitter alignment.

c. Resistance to deterioration resulting from exposure to temperature-humidity cycling.

2.4.2 Experimental Effort

Efforts to design a coating which anti-reflected KBr from 5 to 30μ and also protected it were not successful. The next best solution was to design a protective film which affected the beamsplitter performance from 5 to 30μ as little as possible. A system of PbF_2, ZnS, and $ThOF_2$ gave best all around optical and mechanical results. The coating consists of a quarter-half-quarter wave optical thickness stack respectively of the above materials. Design wavelength was 0.6μ where anti-reflection occurs.

2.4.3 Summary of Test Results

Figures 6 and 8 show the visible and infrared transmission characteristics of the protective film on KBr. This coating satisfied the optical requirements and was able to withstand 70% ±3% relative humidity at 30°C for 24 hours. Other characteristics are summarized in the test data sheets for PbF_2, ZnS, and $ThOF_2$ contained on the previous pages.

2.4.4 References (Section II)

(1) R. Jacobsson, Optica Acta, Vol 10 No. 4 (Oct. 1963)

(2) P.H. Berning, J. Opt. Soc. Am. 52, 431 (1962)

(3) L.I. Epstein, J. Opt. Soc. Am. 42, 806 (1952)

SECTION III

DISCUSSION OF PHASE II EFFORT

3.1 SUMMARY OF PHASE II OBJECTIVES

Phase II was concerned with the fabrication of a prototype beamsplitter and compensating element. After fabrication, elements were tested for optical performance and mechanical stability.

3.2 FABRICATION OF PROTOTYPE BEAMSPLITTER

Coating films for the beamsplitter were evaporated by standard resistance heating techniques. Film thicknesses were optically monitored with a Perkin-Elmer designed modulated beam photometer. Generally, a technique of recording multiples of quarter wave optical thickness provided necessary controls. When films became too thin to adequately monitor using optical techniques a "Sloan Instrument" crystal oscillator monitor was used. The monitor had previously been calibrated against the Perkin-Elmer optical monitor.

Evaporations were made in a CVC Model LC1-18B coating unit with pyrex bell jar and 1440 liters/sec diffusion pump. Maximum pressure during coating was 5×10^{-5} Torr.

Normal precautions were taken in the handling and coating of soluble and toxic materials. In all 110 coating experiments were performed to develop an adequate IR beamsplitter.

SECTION IV

DISCUSSION OF PHASE III EFFORT

4.1 SUMMARY OF PHASE III OBJECTIVES

Phase III was concerned with the design, fabrication and testing of prototype and production beamsplitter mounts. Mounted beamsplitters were tested for their survival ability and performance characteristics. Components were redesigned as required and three mounted beamsplitters were fabricated and delivered to NASA-Goddard.

4.2 DESIGN OF BEAMSPLITTER MOUNT

4.2.1 Design Requirements

The mounting arrangement for a functional beamsplitter system must contain the substrate and compensator elements without any optical or mechanical degradation during vibration, acceleration and thermal environments, and be compatible with the specified external dimensional limitations.

The mount required to meet specifications stated in NASA RFP PC 651-41849/264 was limited in size, as shown in Figure 17. Within these specifications, the interface between the optical elements and the mounting structure was to be designed. A primary criteria for the design was to securely restrain the optical crystals selected without impairing their dimensional stability. The remaining criteria for the design of the mount required consideration of the following environmental conditions:

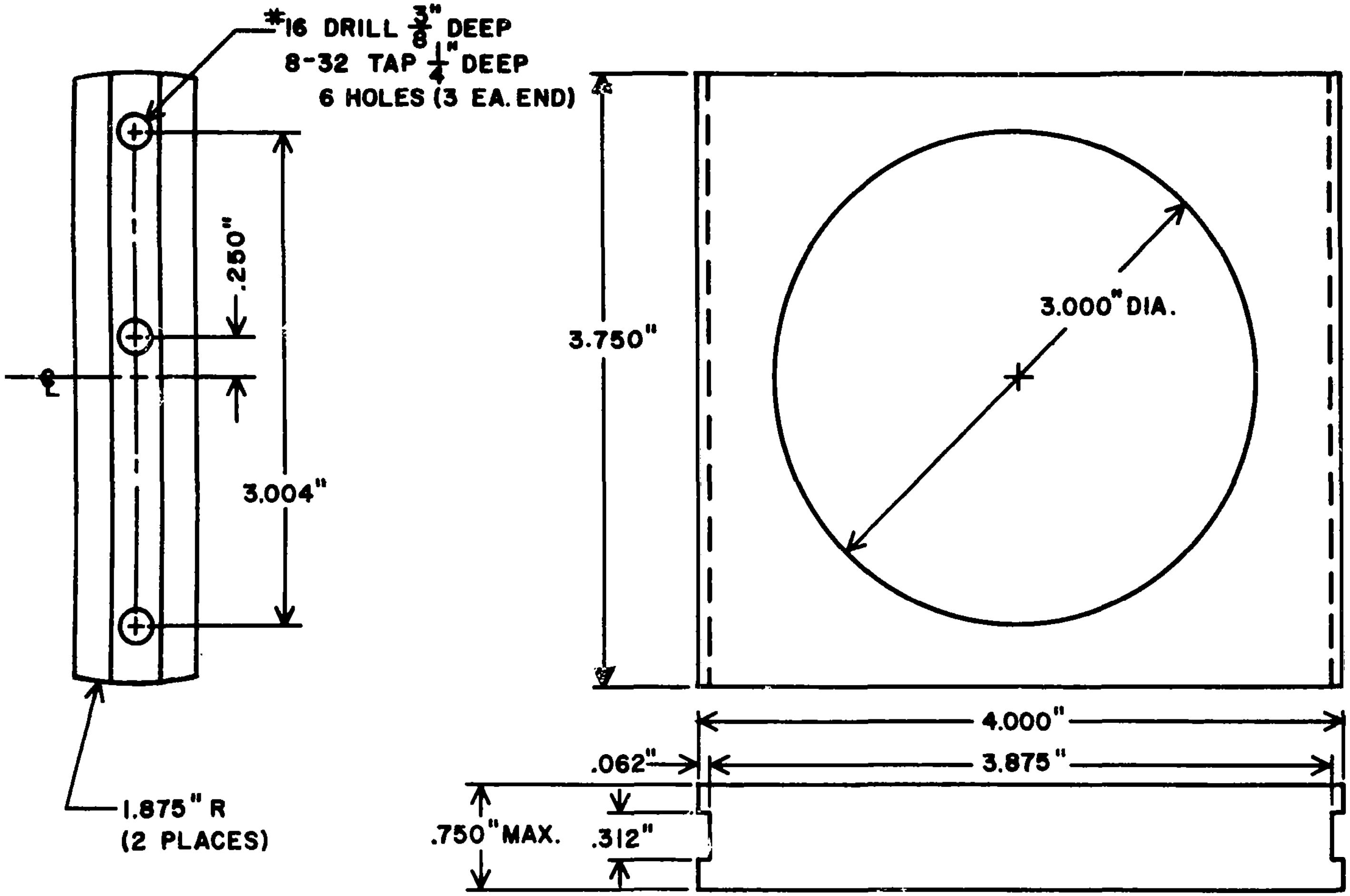


Figure 17. Dimensional Requirements for Beamsplitter Mount

Sinusoidal vibrations of 0.4" DA from 5-22 cps and 10 G (peak) ±10% from 22 to 2,000 cps, swept at a rate of 28 sec per octave, for a total of 4 minutes in the plane of each of three mutually perpendicular axes.

Random motion vibration of 20 G (rms) + 10% -0.0% (20-200 cps) for a period of four minutes in each of the three mutually perpendicular axes.

Sustained acceleration of 30 G for a period of five minutes in each of the three mutually perpendicular axes.

Temperature cycle for four 8-hour days to range from -25° C to +55° C at a maximum rate of 0.25°C per minute in a vacuum of 10^{-5} mm Hg maintaining the lowest and highest temperature for two hours.

Sustained temperature cycling from 0.0° C to 30° C in air for seven 8-hour days and in a vacuum of 10^{-5} mm Hg or lower for seven 8-hour days maintaining the lowest and highest temperature for two hours.

4.2.2 Design Procedure

The solution to the problem of restraining the substrate and compensator beamsplitter elements evolved with a theoretical approach which led to the construction of the engineering prototype. This prototype was then used to test the theoretical analysis, and to obtain additional data on crystal stability and sensitivity to applied loads. This prototype was also used to evaluate the design concept by subjecting it to actual environmental tests. Equipped with this additional information, a slight change to the mount structure was incorporated into a corrected assembly procedure to achieve the final mount design. A revised beamsplitter system was then fabricated and subjected to an abbreviated environmental test and evaluated. On the basis of this test, which proved the mounting system to be satisfactory, the remaining units were fabricated. A beamsplitter system was then subjected to the entire environmental specification as qualification for acceptance.

4.2.2.1 Theoretical Approach

An initial investigation indicated that two possible solutions for beamsplitter mounting arrangements existed that would satisfy the survival of launch shock and vibration requirements. These possibilities arose from the fact that a range of vibration excitation exists above and below the specified input frequencies. The primary objective, therefore, for efficient vibration design was to prevent the lowest natural frequency of the beamsplitter elements from occurring within the range of input excitation. If this were accomplished, a possible resonance condition could be avoided. The lowest natural frequencies of typical beamsplitter elements of 0.3" in thickness and 3.0" in diameter were determined and are as follows:

Element		Natural Frequency (f_n)
Cesium Iodide	=	1,400 cps
Potassium Bromide	=	4,130 cps
Thallium Bromide	=	3,250 cps

At a resonance the input forces tend to be amplified to the extent that either a limit is reached due to the amount of damping in the system, or fracture of the element occurs. Since the yield stress for each of these materials is known, the maximum permissible amplification could then be determined. The results are illustrated by the curves for the three beamsplitter materials plotted in Figure 18. The vibration characteristics, therefore, indicate that the mount's natural frequency should be below five cycles per second or above 2,000 cycles per second. If the design frequency were low, the elements would have to be contained by very resilient members with a spring rate of approximately 0.4 lbs per inch. The restrictions on this however are the lack of physical space and the high alignment accuracy that must be maintained. Therefore, the hard mount or high natural frequency system is the most desirable. The use of a thin layer (which would not alter the spring rate) of high damping visco-elastic material such as RTV-60 between the elements and the metal mount would provide some degree of damping for all frequencies. The mount itself should be constructed of high spring rate or high stiffness material such as stainless steel or beryllium. The actual mounting planes should be sufficiently accurate so as to prevent a non-uniform restraining force which would cause non-uniform strain and therefore a change in optical figure. For preliminary beamsplitter elements, the allowable stress in each element required to produce a deflection of 0.4μ (the maximum allowable) was calculated, and are as follows:

Element	Stress
Cesium Iodide	2.88 psi
Potassium Bromide	15.8 psi
Thallium Bromide	34.2 psi

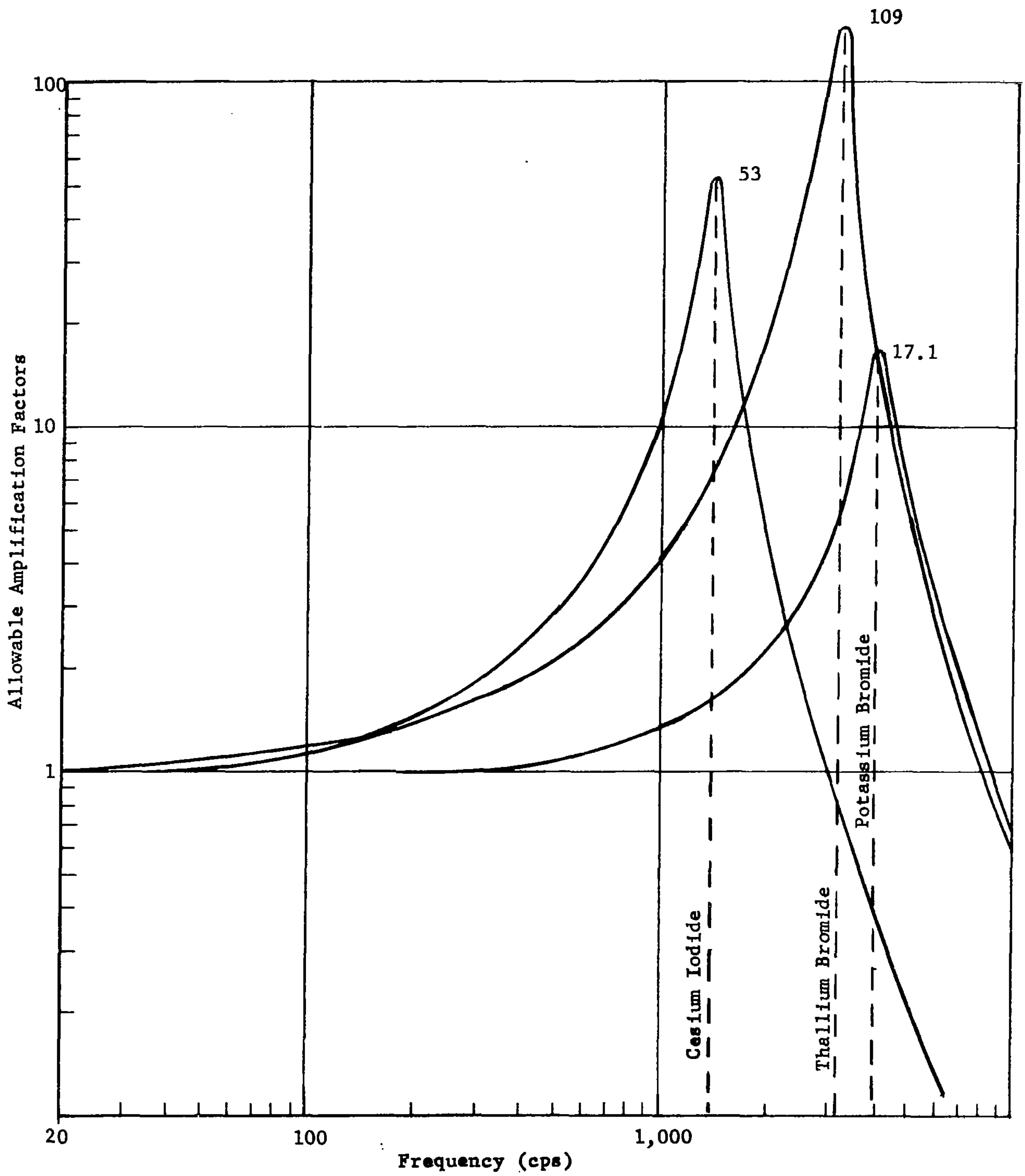


Figure 18. Resonance Curves for Typical Beamsplitter Elements

The thermal coefficients of expansion for the beamsplitter elements are such that they cannot be matched by the metal mount. However, the visco-elastic material separating the elements from the metal will compress or absorb the difference in expansion thereby minimizing thermal stresses in the optical elements.

Due to the fact that the primary function and nature of the mount is mechanical, its properties should be given consideration with the mechanical properties of beamsplitter element materials. A summary of the mechanical properties of the typcial materials considered follows:

	Density	Coefficient of Thermal Expansion	Modulas of Elasticity	Yield Stress
CsI	.163 lb/in^3	50×10^{-6} in/in/°C	7.69×10^5 psi	810 psi
KBr	.0994 lb/in^3	43×10^{-6} in/in/°C	3.9×10^6 psi	160 psi
TℓBr	.269 lb/in^3	51×10^{-6} in/in/°C	4.28×10^6 psi	3,000 psi

4.2.2.2 Engineering Analysis

To assure the capability of the mount, a detailed analysis was performed to establish minimum design dimensions or criteria. Since a mount structure with a high natural frequency response was established as the most logical approach, the minimum spring rate of the mounting flanges was calculated. For potassium bromide elements the minimum axial spring rate was found to be 2×10^5 pounds per inch. Using this value, a further analysis revealed that the minimum flange thickness was found to be 0.045". Under these conditions, therefore, the axial vibration amplification would be limited to 1.0. As a check on the possible fracture of the beamsplitter elements the stresses on each element subjected to a 10G load were determined as follows:

Element	Stress
Cesium Iodide	15.3 psi
Potassium Bromide	9.34 psi
Thallium Bromide	27.6 psi

The stresses determined to result from the application of an applied constant acceleration of 30 G's are as follows:

Cesium Iodide	46 psi
Potassium Bromide	27 psi
Thallium Bromide	83 psi

If a clamping force of 3 pounds were used to restrain the elements in the mount, a stress of 1.26 psi would result. To assure uniform clamping, a minimum value of torque to be applied to the cover bolts was found to be approximately 5 in. bls. and a minimum bolt length required to deter axial resonance was found to be 1/4".

4.2.2.3 Mount Construction

Because of the rigidity required in the mount structure, it was decided to make the main body as uniform as possible. A flat cover plate was then used to enclose the 3-1/4" diameter cavity required for the elements. A clear aperture of 2-5/8" in diameter was then provided by the 2-3/4" diameter hole through both the main body and cover plate. The circular flanges on which the elements rested were machined both flat and parallel to .001". Eight screws were provided to fasten the cover plate to the main body so as to uniformly distribute the clamping force. The exterior dimensions and details were as required.

4.3 FABRICATION OF FINAL BEAMSPLITTER ASSEMBLY

Many problems were encountered during the fabrication of the prototype beamsplitter mount. After extensive experimentation and design analysis the mount and assembly procedure were redesigned and finalized.

The improvements which were established by the experimentation and incorporated in the redesign are as follows:

(a) An increase in the thickness of the beamsplitter elements from 0.3 inch to 3/8 inch.

(b) An increase in thickness in the mounting structure from 3/4 inch to 1 inch.

(c) An increase in the thickness of the mounting flanges to 0.125 inch and an improved means of machining and maintaining their flatness to 0.0002.

In the redesign of the mount, a NASA request for four additional mounting holes and four clearance milled slots was complied with. The resulting structure is illustrated in Figure 19 (Perkin-Elmer Drawing 510-2615). The vibration test fixture which remained unchanged is illustrated in Figure 20 (Perkin-Elmer Drawing 510-2626).

Results from the experiments also showed that a revision of the assembly procedure was necessary. Much improvement was effected by considerably reducing the amount of clamping preload. Further improvement was gained by maintaining a separation between the substrate and compensator and by controlling the thickness and flatness of the RTV in the mount. These were

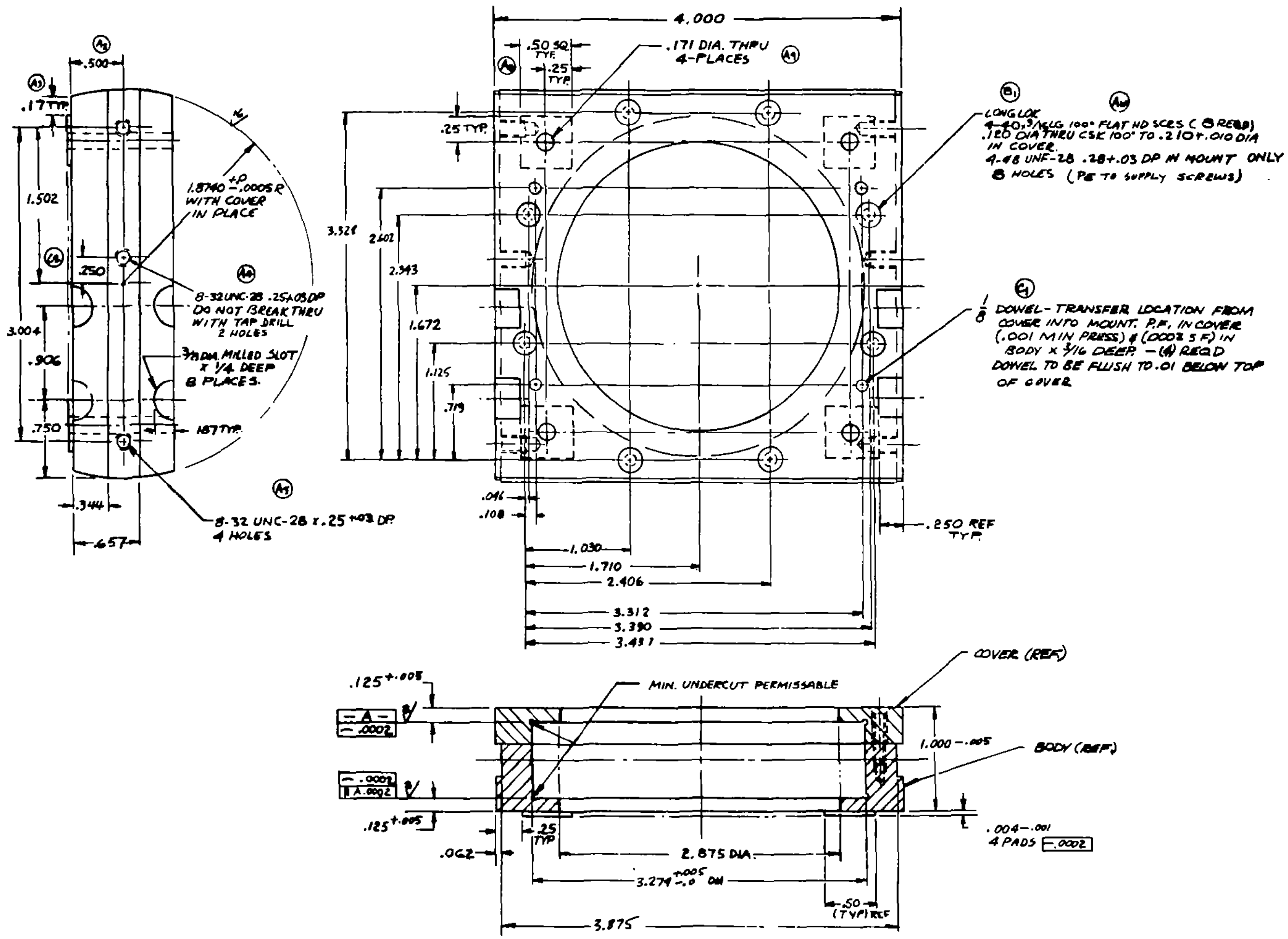


Figure 19. NASA-Goddard-Interferometer Beamsplitter Mount

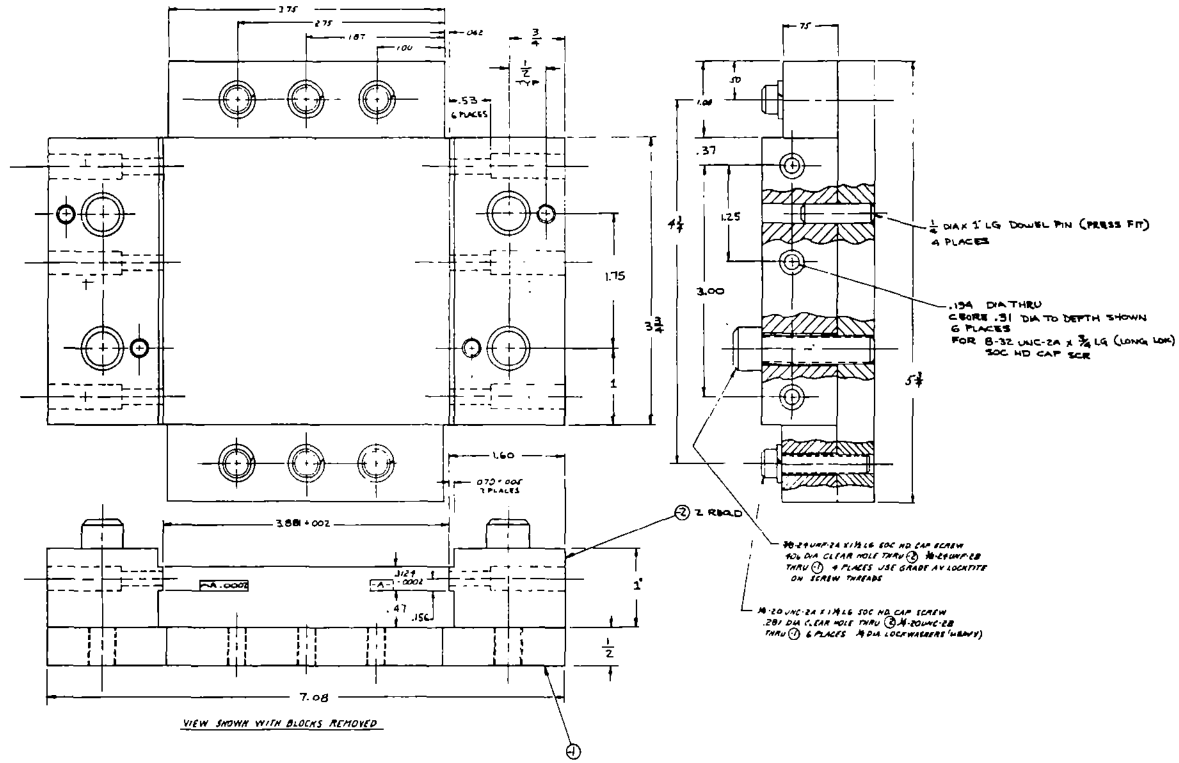


Figure 20. Shake Table Fixture Beamsplitter Mount

accomplished by conforming to the following assembly procedures, illustrated in Figure 21 (Perkin-Elmer Drawing 510-2621).

(1) The height of the mount cavity is measured to find its exact dimension after tolerance.

(2) Substrate and compensator crystals are then polished to a desired thickness to allow for 0.003 inch mylar pads between the mount and the compensator, between the compensator and the substrate, and between the substrate and the mount,

(3) The mylar pads are placed 120° apart and are in line through the mount.

(4) Prior to placement of the elements and the cover section, a bead of RTV-60 is applied.

(5) When the cover section is placed on the mount, the elements are not permitted to be compressed more than 0.001 inch.

(6) The screws are then torqued to 15 in. lbs. in the prescribed sequence and the RTV is permitted to cure.

A final beamsplitter assembly was fabricated using the redesigned mount and revised assembly procedure, and subjected to vibration tests and to the required temperature-humidity tests. No degradation of optical figure resulted from these tests.

Dimensional Drawings for the three beamsplitter assemblies delivered are shown in Figures 22 through 24. Individual transmission curves for these assemblies are shown in Figures 25 through 27. (It should be noted that energy not transmitted is reflected, as indicated in Figure 10.)

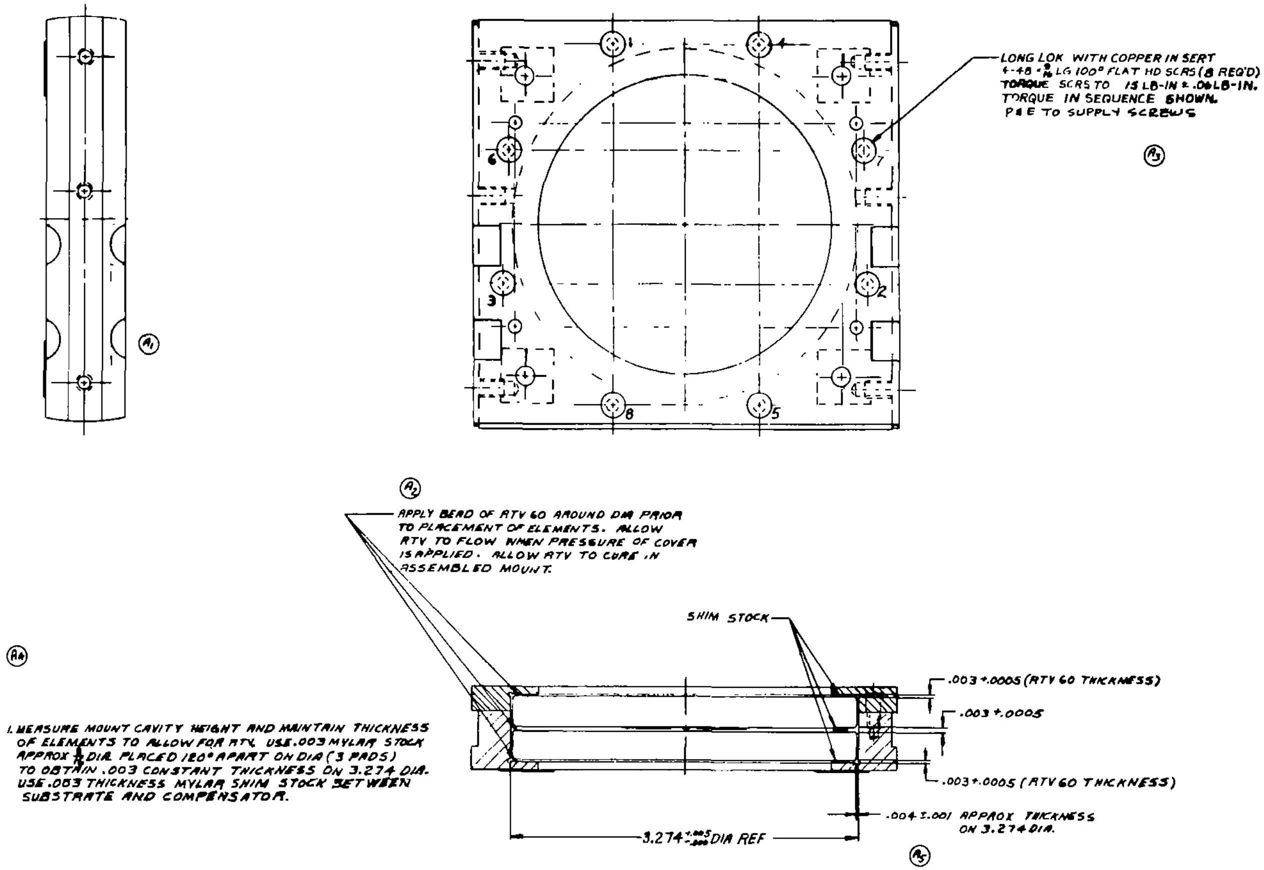
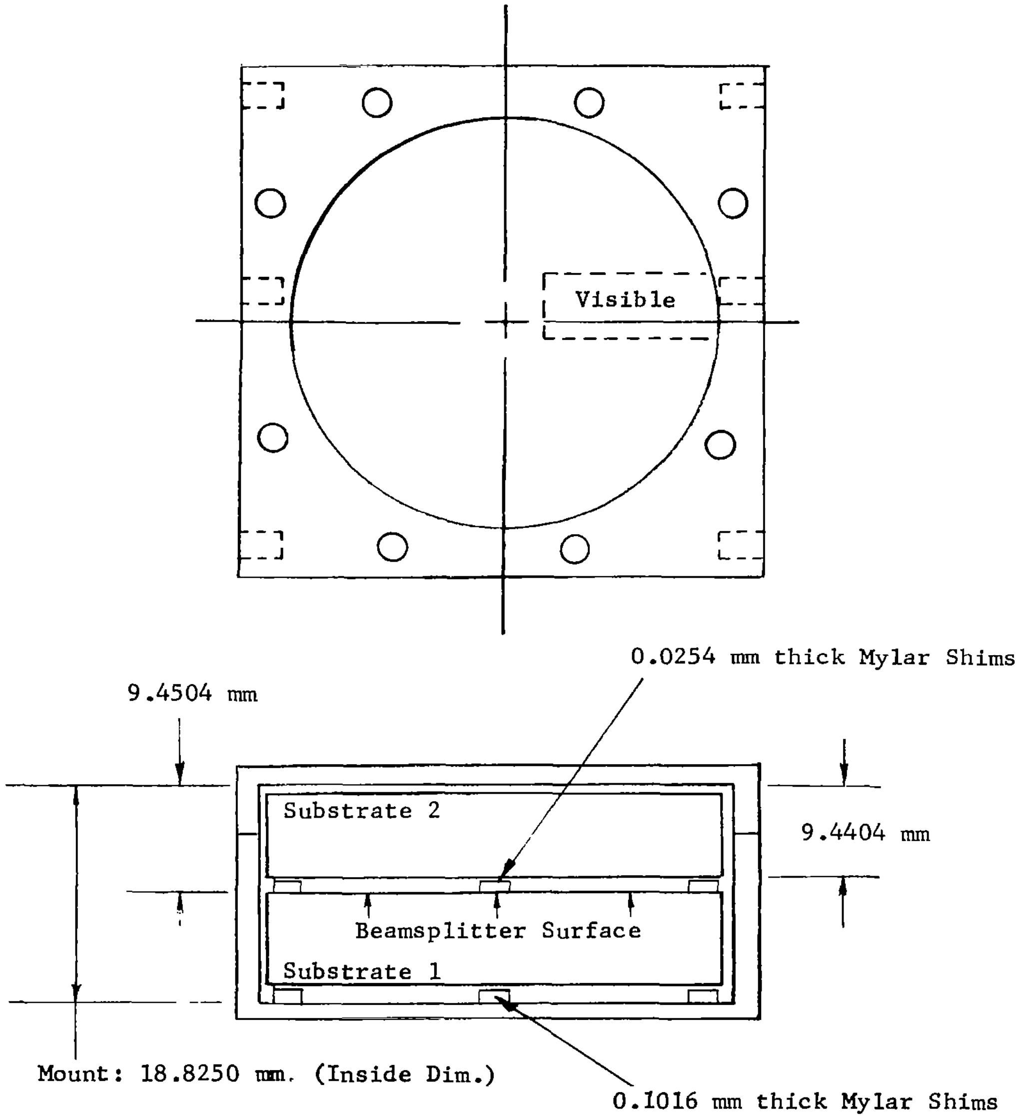
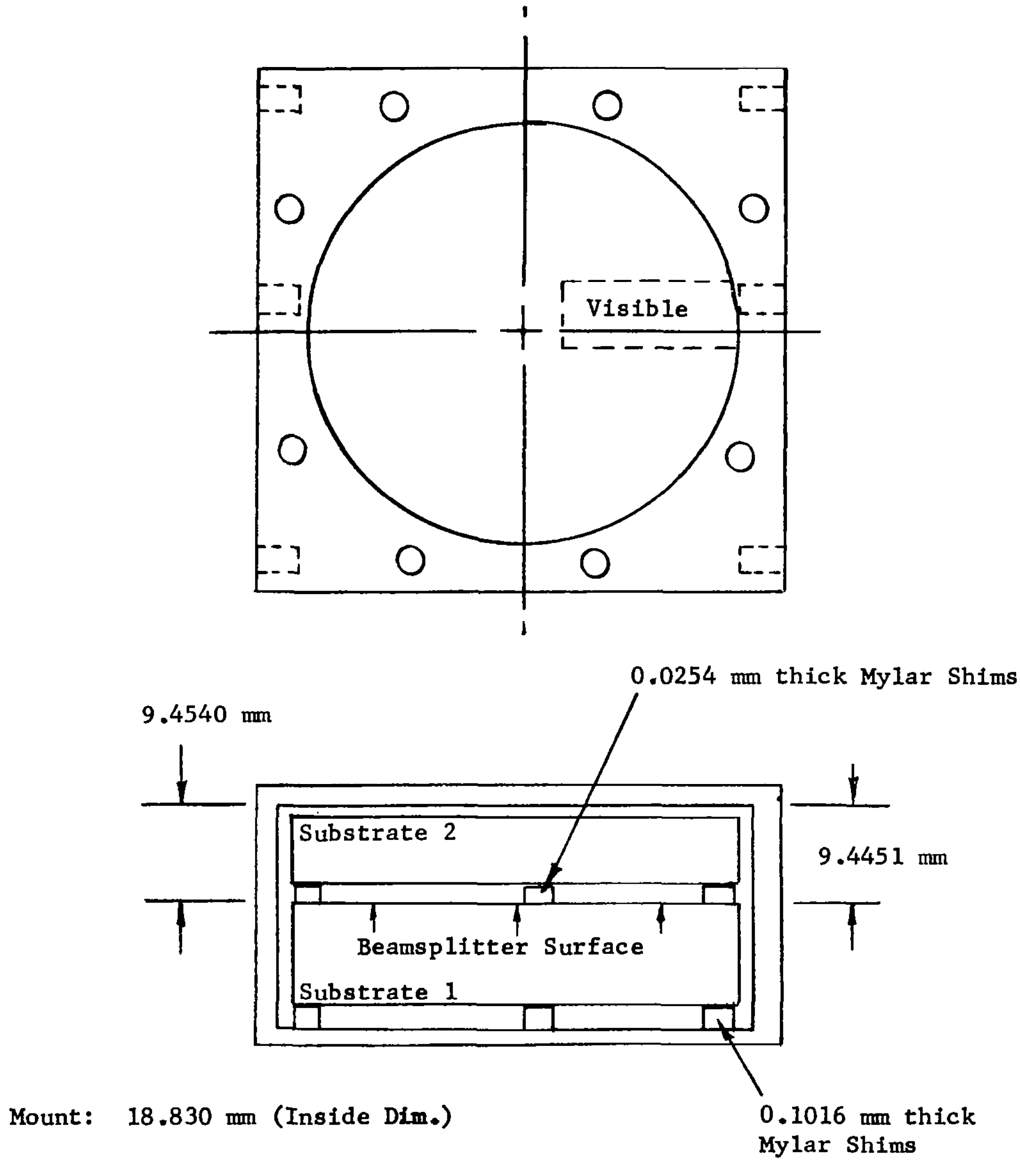


Figure 21. NASA-Goddard-Interferometer Beamsplitter & Mount Assembly Procedure



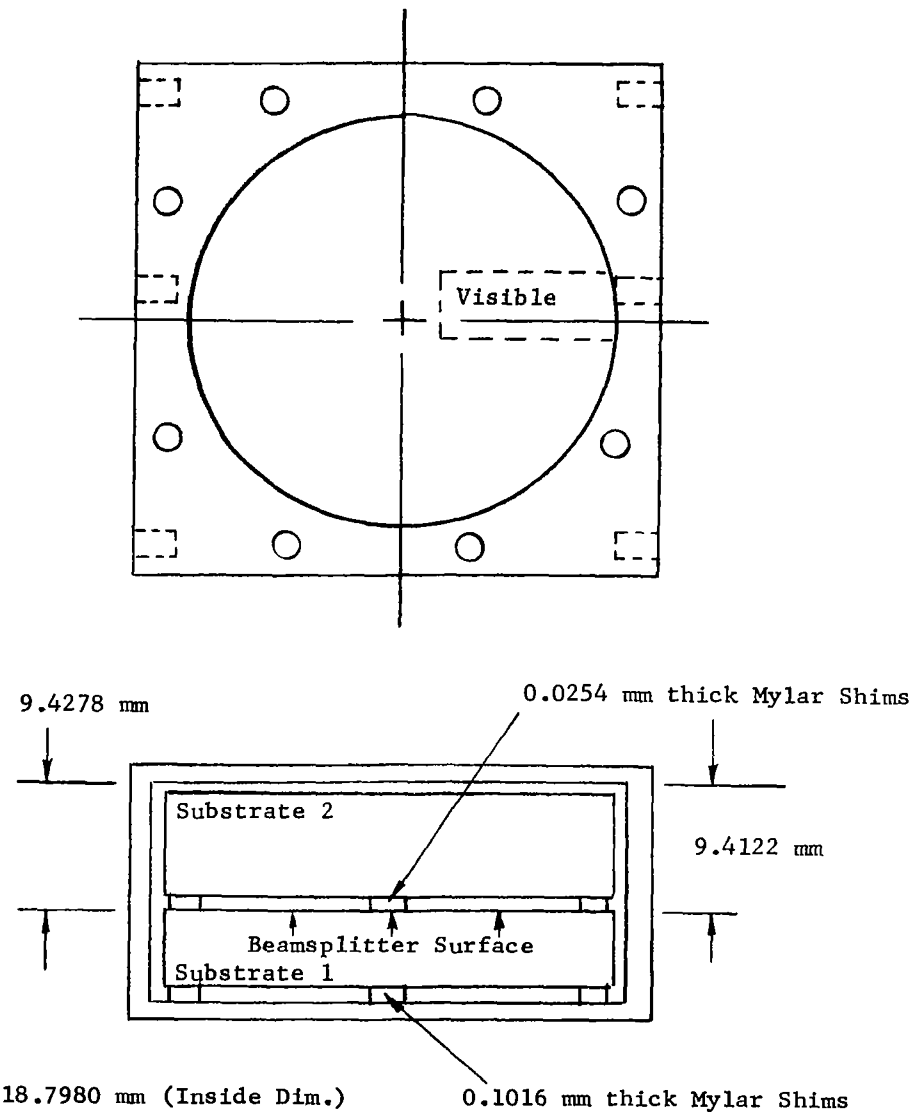
	High	Low
Substrate 1 (BS)	9.2830 mm	9.2730 mm
Substrate 2	9.2879 mm	9.2798 mm

Figure 22. Dimensional Drawing of Beamsplitter Assembly No. 1 (KBr)



	High	Low
Substrate 1 (BS)	9.2833 mm	9.2744 mm
Substrate 2	9.3100 mm	9.2870 mm

Figure 23. Dimensional Drawing of Beamsplitter Assembly No. 2 (KBr)



Mount: 18.7980 mm (Inside Dim.)

	High	Low
Substrate 1 (BS)	9.2842 mm	9.2686 mm
Substrate 2	9.2899 mm	9.2750 mm

Figure 24. Dimensional Drawing of Beamsplitter Assembly No. 3 (CaF_2)

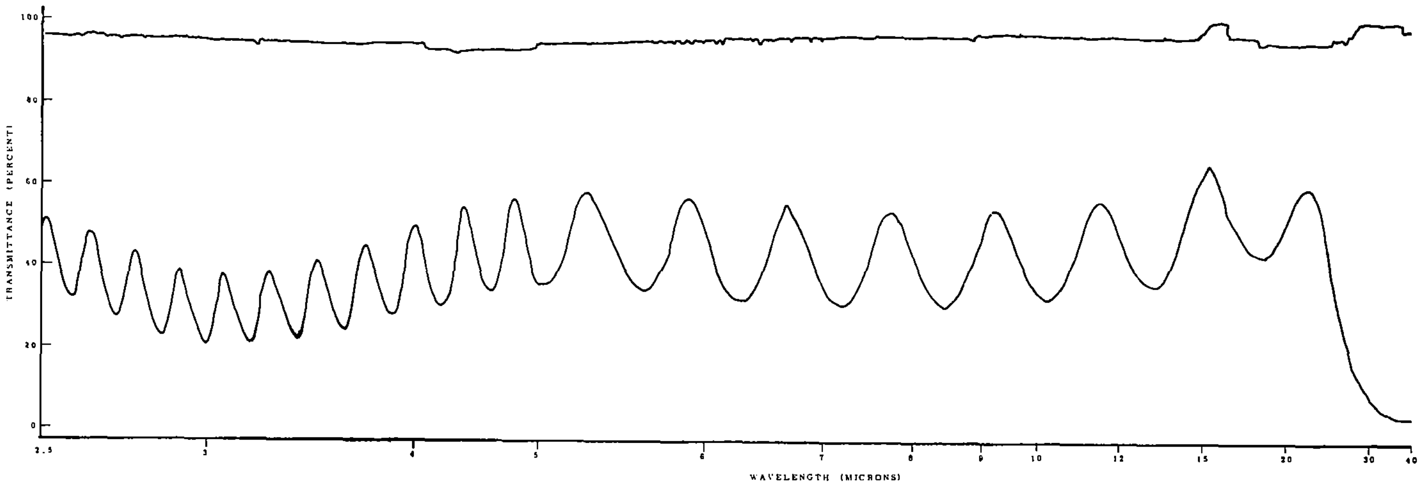


Figure 25. Transmission Characteristics of Beamsplitter No. 1

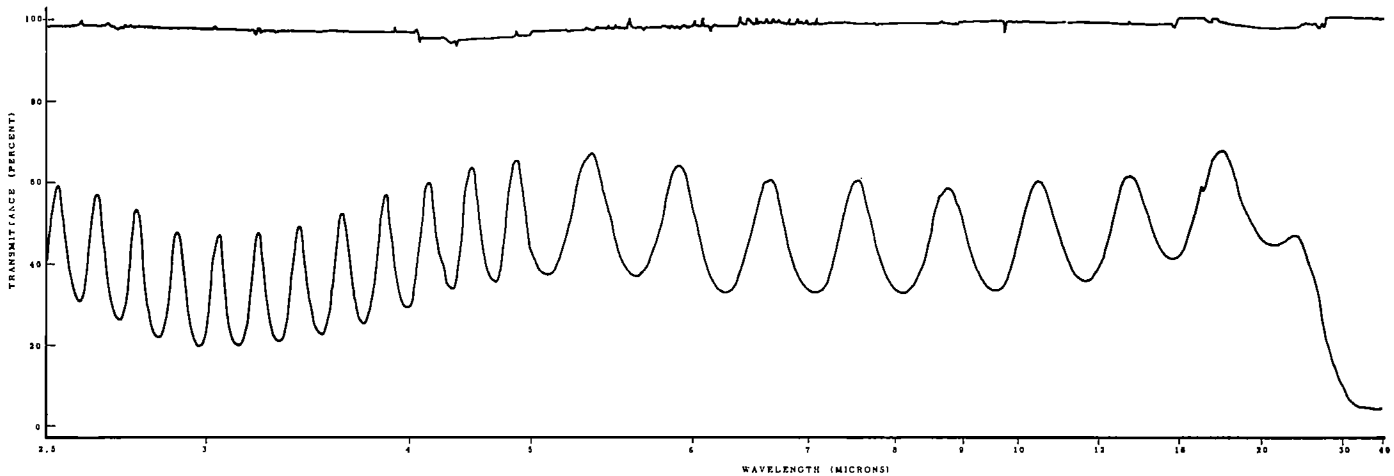


Figure 26. Transmission Characteristics of Beamsplitter No. 2.

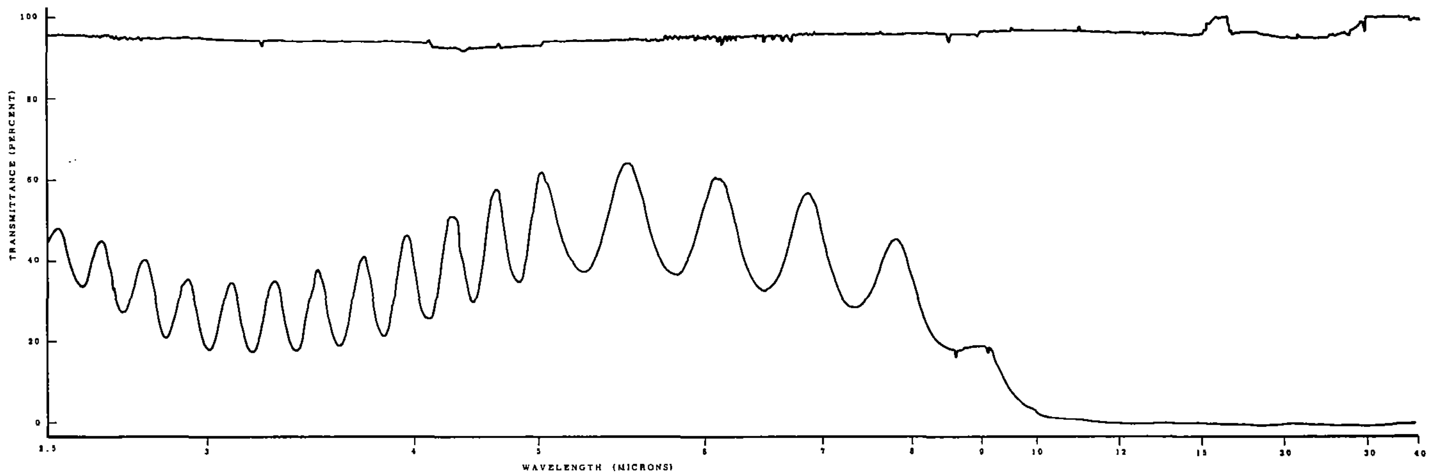


Figure 27. Transmission Characteristics of Beamsplitter No.3.

4.4 SURFACE FLATNESS TESTS DURING TEMPERATURE CYCLING

As part of a one-month contract extension, Perkin-Elmer agreed to perform certain optical tests beyond the scope of the original contract. Basically, the tests consisted of checking the surface flatness of KBr and CaF_2 mounted beamsplitters during temperature cycling.

The straightforward test setup normally used for vacuum heating and cooling was complicated severely by the requirement to make optical measurements during cycling. In order to measure optical flatness of the beamsplitter element visual observations had to be made. This meant that an adequate shroud could not be used for temperature control.

Temperature cycling was accomplished by conduction heating and cooling of one side of the beamsplitter while checking the optical flatness of the second side. Unfortunately the second surface was always exposed to ambient temperatures and, because of the large temperature gradient across the beamsplitter, caution is urged in drawing conclusions from the temperature cycling tests.

4.4.1 Test Procedure

Throughout each test observations were made of optical flatness of the uppermost beamsplitter surface. The method used was the standard test plate procedure for testing optical flatness and was as follows:

(1) A large diameter monochromatic light source was used to illuminate the reference test plate and beamsplitter surface.

(2) A slight wedge was introduced between elements so that a fringe pattern could be observed.

(3) Visual observations were made of changes in fringe pattern during temperature cycling.

Test setups, described below, are shown in Figures 28 and 28.

4.4.1.1 Reference Test Plate

A reference test plate was obtained by the following method. Two flat quartz test plates were placed together in vacuum to determine if optical flatness changed during temperature cycling. The figure at the start was $\lambda/10$ flat over 3 inches. No change in optical flatness was observed. One of the two test flats was used as a reference to check crystal flatness in all subsequent tests.

4.4.1.2 Vacuum Cooling Test Setup

The beasmplitter mount was clamped to a coil of 1/4 inch copper tubing and plexiglass placed under the copper tubing for support. The beam-splitter mount was pressed into good contact with the copper coil. A chromel-alumel thermocouple was mounted on one side of the mount and a graphic recording made of temperature vs. time for each cooling cycle. Cooling was accomplished by circulating liquid nitrogen through the copper tubing. Temperature at the coil was -65° C when the temperature of the mid part of the mount was -25°C.

4.4.1.3 Vacuum Heating Test Setup

The beamsplitter mount was placed on a black anaodized aluminum plate which was heated from below by a nichrome filament. A black anodized

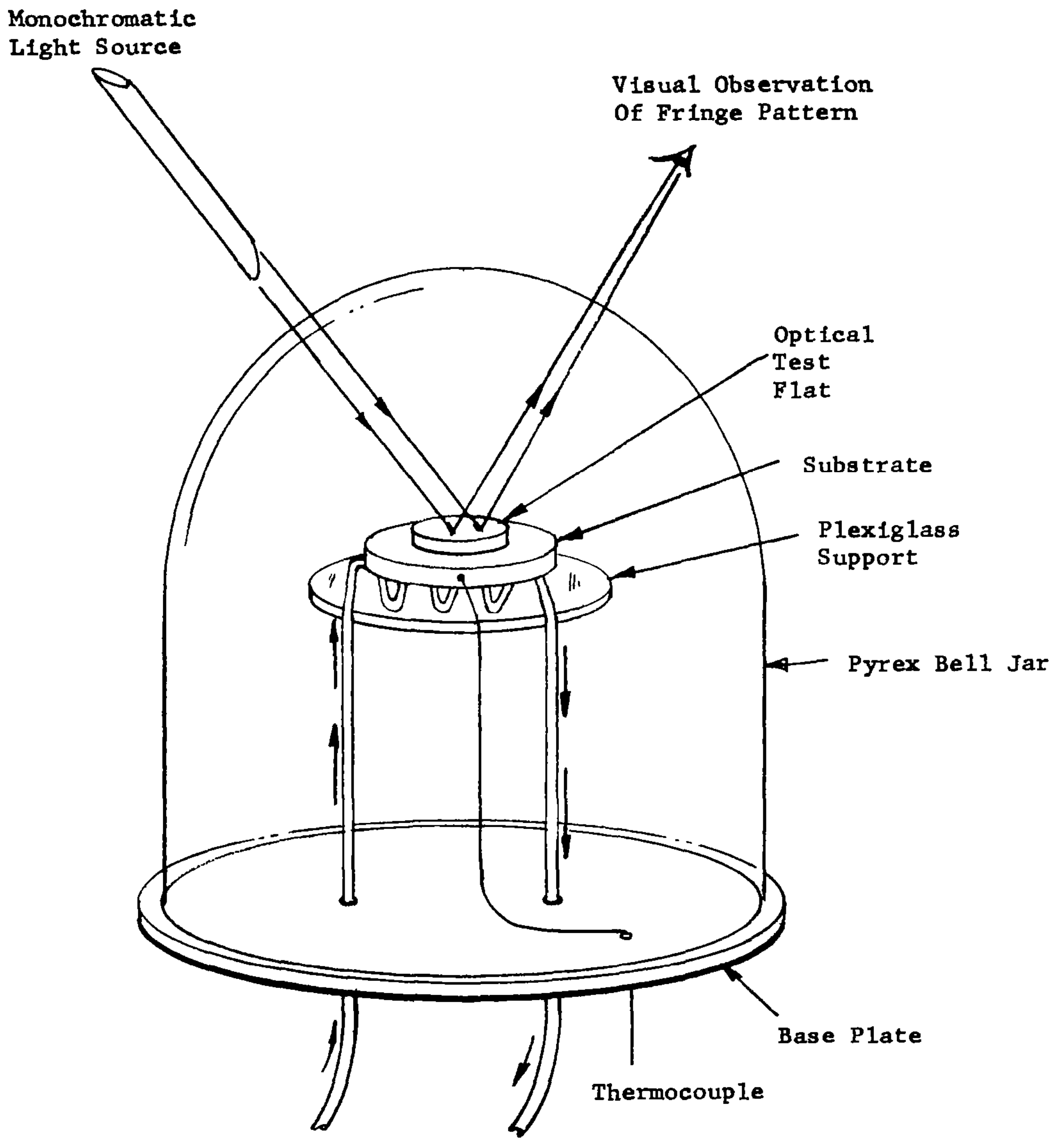


Figure 28. Test Setup for Vacuum Cooling Cycle

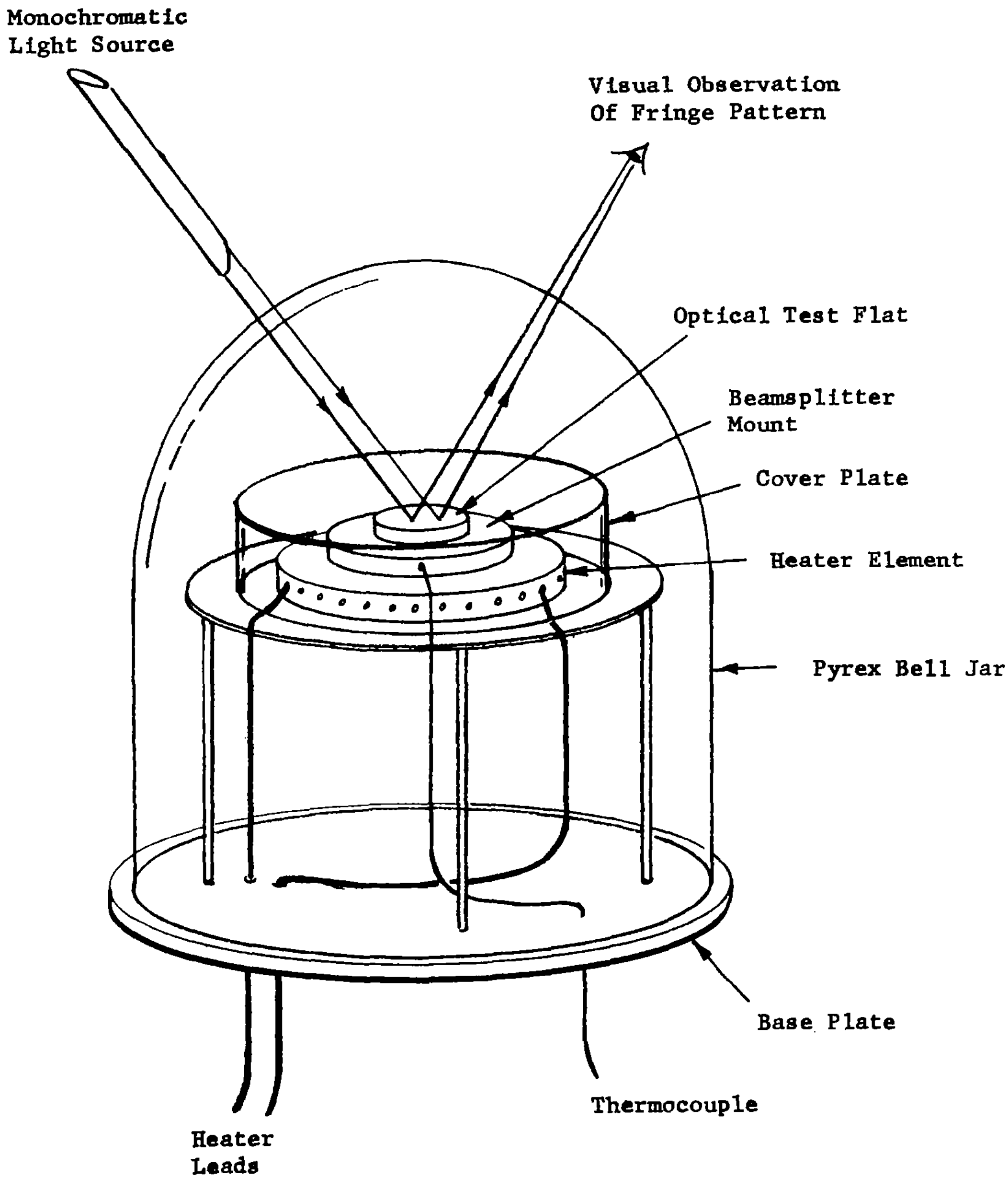


Figure 29. Test Setup for Vacuum Heating Cycle

cylinder 6 inches in diameter and 2 inches high was then placed around the entire setup as a shroud. A chromel-alumel thermocouple again was used at the center edge of the mount to monitor temperature. Observations of fringe change were made during temperature cycling.

4.4.2 Summary of Test Results

4.4.2.1 Temperature Cycling of Mounted CaF_2 Beamsplitter.

The CaF_2 beamsplitter survived all environmental testing without any optical degradation. A typical cycle was as detailed below:

(a) Temperature cycling from -25°C to 55°C at
10^{-5} mm Hg (4 day cycle)

(b) Temperature cycling from 22°C to 0°C to 30°C
7 day cycle in air (dry air bleed)
7 day cycle at 10^{-5} mm Hg

(c) Humidity cycle
24 hours at 30°C at 67% RH

4.4.2.2 Temperature Cycling of Single KBr Crystal

Tests were performed on two KBr samples. A KBr substrate which was polished to within $\lambda/2$ flat on both sides was placed in a mount without shims or RTV silastic. The substrate was cooled at a rate of 1 degree C per minute. The temperature of the mount was brought down to -25°C and maintained for 1 hour. No change in the flatness of the KBr substrate was observed. The substrate was cycled to room temperature in 10 hours.

The second sample was tested in the same manner except that the substrate was brought to -25°C in 1-1/2 hours. No change in optical figure was observed.

4.4.2.3 Cooling Cycle of Mounted KBr

The beamsplitter mount was placed in vacuum. Optical figure at room temperature in vacuum was 1.5λ convex. The temperature of the mount was brought down to 0°C in 30 minutes. The optical figure changed to 2.5λ concave. A temperature of 0°C was maintained for 1 hour without further change in the optical figure.

The mount temperature was then brought down to -25°C in 30 minutes. The optical figure remained the same. The temperature was maintained at -25°C for 1 hour with no further optical change taking place.

The temperature was returned to 22°C in 4 hours. The optical figure returned to its original value 1.5λ convex. Average vacuum pressure during cycle was 5×10^{-6} mm Hg.

The cycle was repeated according to the schedule for 7 days in vacuum and 7 days in air. Changes in flatness described above are representative of maximum changes during 14 day cycling.

4.4.2.4 Heating Cyle of Mounted KBr

The beamsplitter mount was placed in vacuum. The temperature of the mount was increased to 55°C in 2 hours. Optical figure at room temperature in vacuum was 1λ. The figure at 55°C in vacuum was 2λ. A temperature of 55°C was maintained for 2 hours with no further change in optical figure.

The mount was allowed to return to room temperature (22°C) in 10 hours. During this cooling cycle the optical figure returned to 1λ. Average vacuum pressure during run was 2×10^{-5} mm Hg.

Cycle was repeated 4 times and results were the same each time.

4.4.2.5 Conclusions

Surface flatness of CaF_2 was unaffected by the temperature cycling described above.

Surface flatness of KBr did change by as much as 4λ during cooling cycling and 1λ during heating.

Temperature gradients across the beamsplitter were rather large and probably had a marked effect on surface flatness. It is expected that optical flatness would be much better if the mount were uniformly exposed to the same temperature in all directions.

Temperature cycles were quite rapid and prabably over-severe. Figures 30 through 34 illustrate the nature of temperature cycling used. Much slower cycling would undoubtedly add to optical stability.

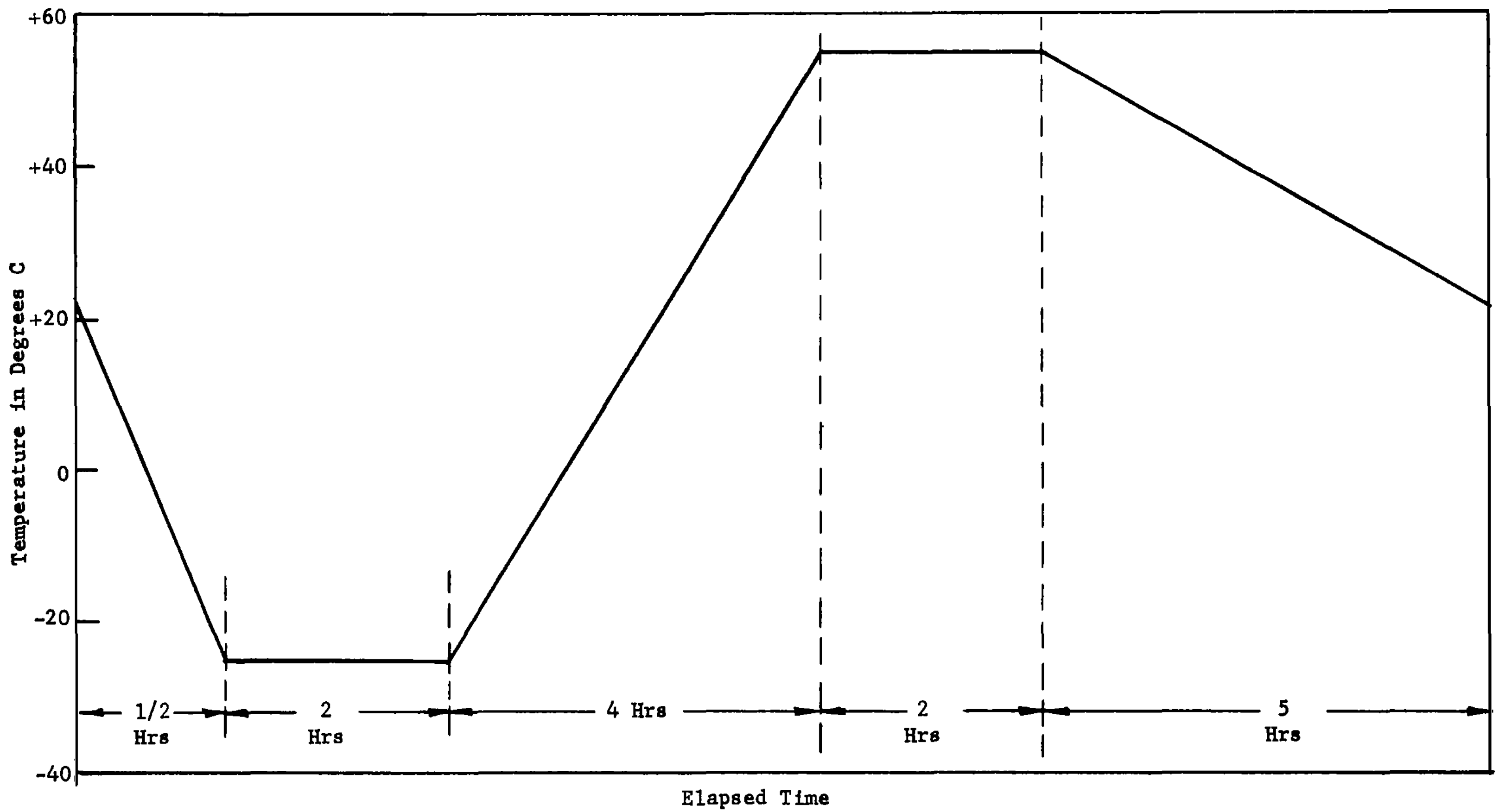


Figure 30. CaF_2 Temperature Profile (4 Day Cycle)

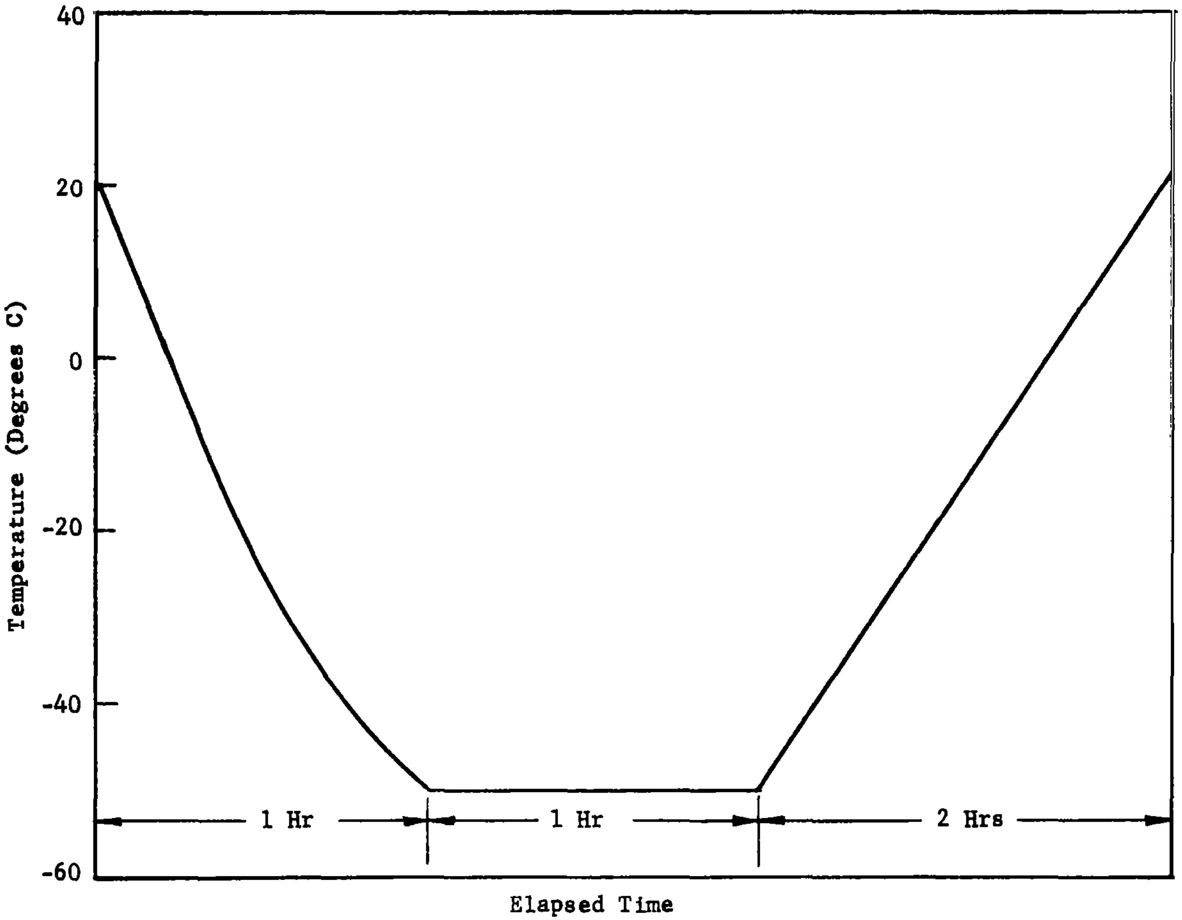


Figure 31. CaF_2 Temperature Profile (7 Day Cycle)

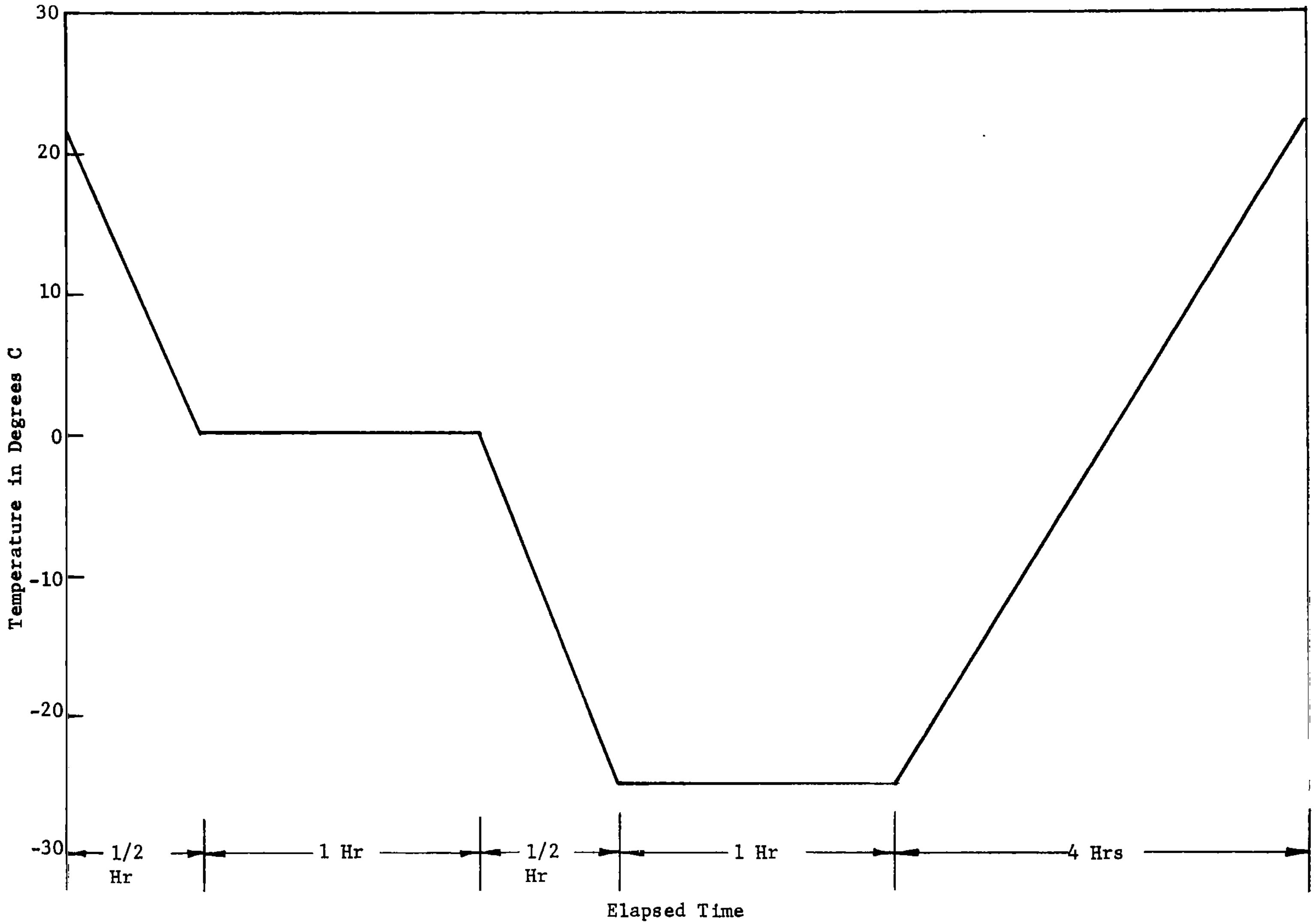


Figure 32. KBr Temperature Profile (4 Day Cycle)

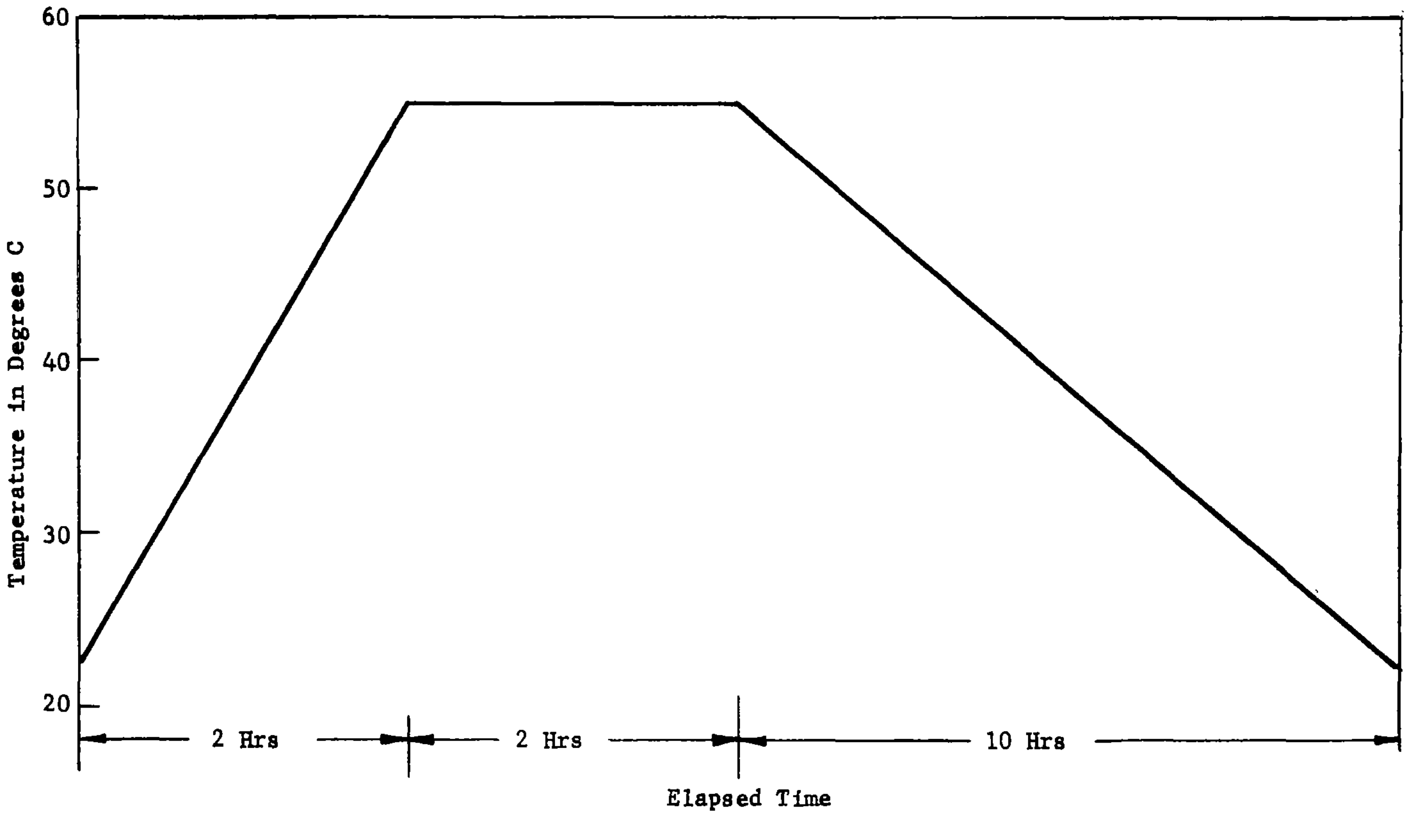


Figure 33. KBr Temperature Profile (4 Day Cycle)

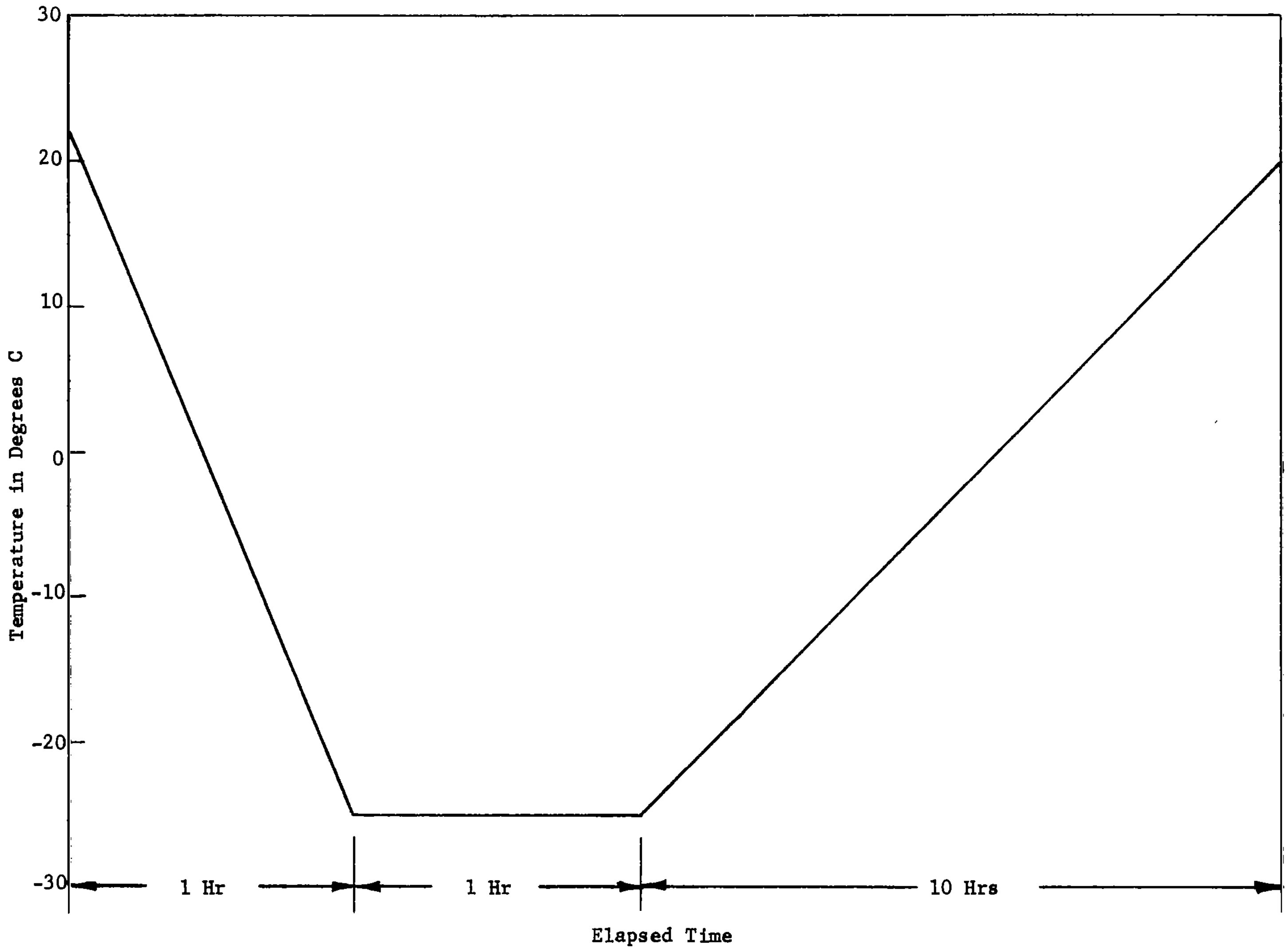


Figure 34. KBr Temperature Profile (7 Day Cycle)

4.5 HANDLING PROCEDURES

The mounted beamsplitter crystals are subject to damage from many sources. The following procedures are recommended for longest beamsplitter life.

(1) Store mounted beamsplitter in a desiccated dry box when not in use.

(2) Protect the optical faces by taping a plexiglass cover over each face.

(3) When in use take care to avoid dropping the assembly. Handle with finger cots or clean rubber gloves when there is danger of the fingers contacting the optical surfaces.

(4) Avoid unnecessary abrupt temperature changes. This may cause undue machanical strain in the crystals and possible water condensation which may ruin the optical surface.

(5) Do not attempt to clean the optical surfaces by wiping. Dust may be removed by blowing with clean dry air at 10-15 psi.

(6) Do not attempt to disassemble the beamsplitter elements. It will not be possible to reassemble them within required spacing tolerances.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

An all-dielectric beamsplitter for use in an infrared interferometer spectrometer was successfully designed, fabricated and delivered. Its operational range is 5 to 30μ. The beamsplitter performs satisfactorily under simulated environmental conditions such as would be encountered in earth orbiting vehicles.

Weathering tests have shown that the beamsplitter consistently survives 70% ±3% relative humidity for 24 hours at 30°C. Work could be performed to improve performance at relative humidity levels approaching 95%.

One important disadvantage of a potassium bromide supported beamsplitter is the problem of substrate absorption beyond 22μ. The transmission of KBr is practically zero at 35μ. It would seem that a natural extension of the present work would be the design, development and fabrication of an unsupported beamsplitter (substrateless). Such a system could extend operational range to at least 50μ, eliminate the need for path length compensating elements, and generally increase system performance while decreasing weight.

SECTION VI

NEW TECHNOLOGY

The work performed under this contract (NAS5-9560) has resulted in the development and fabrication of a successful broadband infrared beamsplitter, suitable for use in an infrared interferometer spectrometer (IRIS) for the NIMBUS B satellite program.

The accomplishments considered reportable under New Technology are as follows:

(1) Development of a multilayer beamsplitter film system yielding nearly equal broadband infrared reflectance and transmittance.

(2) Development of protective coatings for highly water-soluble crystals used as substrates (viz., potassium bromide) such that the material withstands 70 percent ±3 percent relative humidity for 24 hours at 30°C.

Details are contained in this Final Report under the subject contract for an Infrared Beamsplitter.

APPENDIX A

SUBCONTRACTED VIBRATION TEST REPORT

YORK RESEARCH CORPORATION
STAMFORD, CONNECTICUT

GENERAL OFFICES
ONE RESEARCH DRIVE

CERTIFIED REPORT TRANSMITTAL

DATE SENT: February 10, 1966

METHOD: First Class Mail

COMPANY NAME AND ADDRESS: Perkin-Elmer Corporation
Main Avenue
Norwalk, Connecticut

ATTENTION: Mr. Joseph Iorio

REPORT NUMBER: Y-5600-2 ADDITIONAL COPIES: ______

DISPOSITION OF UNITS Returned to Client

DATE: ______

METHOD: ______

The above referenced report is enclosed. Copies of this report and supporting data, will be permanently retained in our files in the event they are required for future reference.

If there are any questions concerning this report, please do not hesitate to contact either the project engineer Michael Kiyak or the writer.

Naturally, as in the past, our staff will be pleased to quote on any future requirements you may have.

Very truly yours,

YORK RESEARCH CORPORATION

Jeremiah J. McCarthy

Jeremiah J. McCarthy, Manager
Environmental Testing Division

REPORT NO. Y-5600-2 DATE 2/9/66

SUBJECT RANDOM VIBRATION TEST ON ONE (1) INFRARED BEAMSPLITTER

CLIENT PERKIN-ELMER CORPORATION
NORWALK, CONNECTICUT

1.0 ADMINISTRATIVE DATA

1.1 DATE: February 7, 1966 DATE TEST COMPLETED: January 25, 1966

1.2 TEST REPORT NUMBER: Y-5660-2

1.3 PURPOSE OF TEST: To subject an Infrared Beamsplitter to a Random Vibration Test as part of a Qualification Test.

1.4 MANUFACTURER: Perkin-Elmer
Main Avenue
Norwalk, Connecticut

1.5 MANUFACTURER'S MODEL/PART NUMBER: X510-2615
AND SERIAL NUMBER: N.A.

1.6 REFERENCE SPECIFICATION: Perkin-Elmer Qualification Test Procedure for Infrared Beamsplitter, Report No. 8248

1.7 QUANTITY OF ITEMS TESTED: One

1.8 SECURITY CLASSIFICATION OF ITEMS: Unclassified

1.9 TEST CONDUCTED BY: York Research Corporation
One Research Drive
Stamford, Connecticut

1.10 TEST CONDUCTED FOR: Perkin-Elmer

1.11 PURCHASE ORDER NUMBER: 22360

1.12 GOVERNMENT CONTRACT NUMBER: NA55-9560

1.13 DISPOSITION OF TEST SPECIMEN: Returned to Client

1.14 SURVEILLANCE ENGINEER: Joseph Iorio

2.0 ABSTRACT:

One Infrared Beamsplitter was subjected to a Random Vibration Test per Perkin-Elmer Qualification Test Procedure for Infrared Beamsplitter, Report No. 8248. The condition of unit following vibration was determined by Perkin-Elmer personnel.

3.0 EQUIPMENT LIST

	NAME	MANUFACTURER	INVENTORY NO.	SERIAL NO.	DATE OF CALIBRATION	CALIBRATION DUE DATE
3.1	Electrodynamic Vibrator	M.B. Electronics	Y-466	C-126	1/3/66	4/3/66
3.2	Accelerometer	Endevco	JH14	222 c/c	11/4/65	2/4/66
3.3	Vibration Fixture	Perkin-Elmer	Client supplied unit			

4.0 VIBRATION TEST

4.1 PROCEDURE:

The test was performed in accordance with para. 4.3.3 of Perkin-Elmer Qualification Test Procedure for Infrared Beamsplitter, Report No. 8248.

4.1.1 The test fixture was mounted to the table of a C-126 vibrator. A dummy load was mounted to the fixture and equalization was achieved by means of an 80 channel automatic system. (See Figure 1).

4.1.2 The dummy load was removed and the Beamsplitter was mounted to the fixture, and subjected to an RMS Level of 20 g's over a frequency range of 20 to 2000 cps for four (4) minutes a plane in each of three (3) mutually perpendicular planes. The total vibration time was twelve (12) minutes. The orientation of unit was as shown in Figures 3 and 6 of Perkin-Elmer Report No. 8248. A Power Spectrum Density plot was recorded for each plane of vibration. (See Fig. II, III and IV). The axis noted on these charts are as indicated in Perkin-Elmer Report No. 8248.

4.1.3 Following each plane of the test, the Infrared Beamsplitter was physically examined by a member of Perkin-Elmer Optical Meterology Group.

4.2 RESULTS:

The results of the test were determined by Perkin-Elmer.

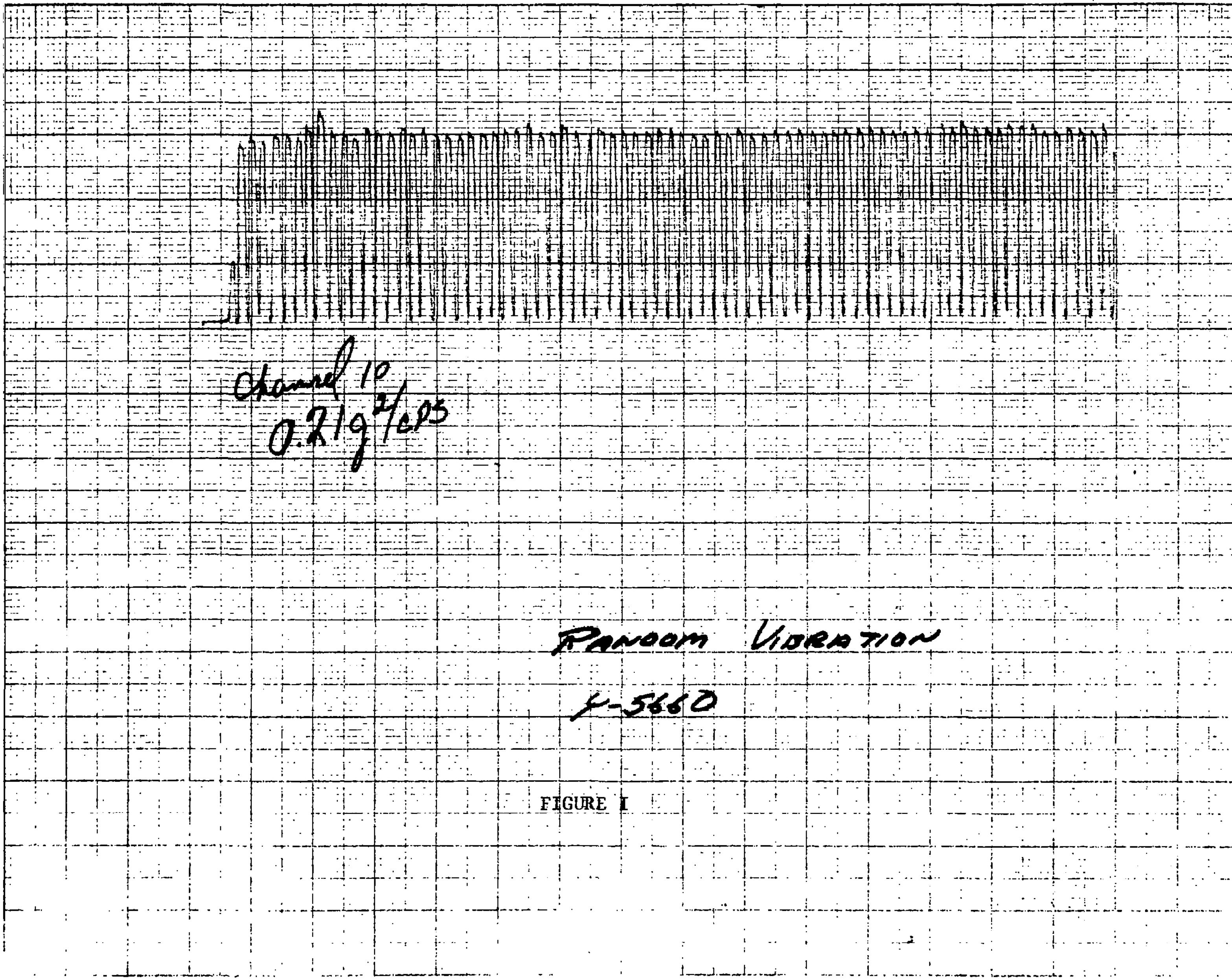
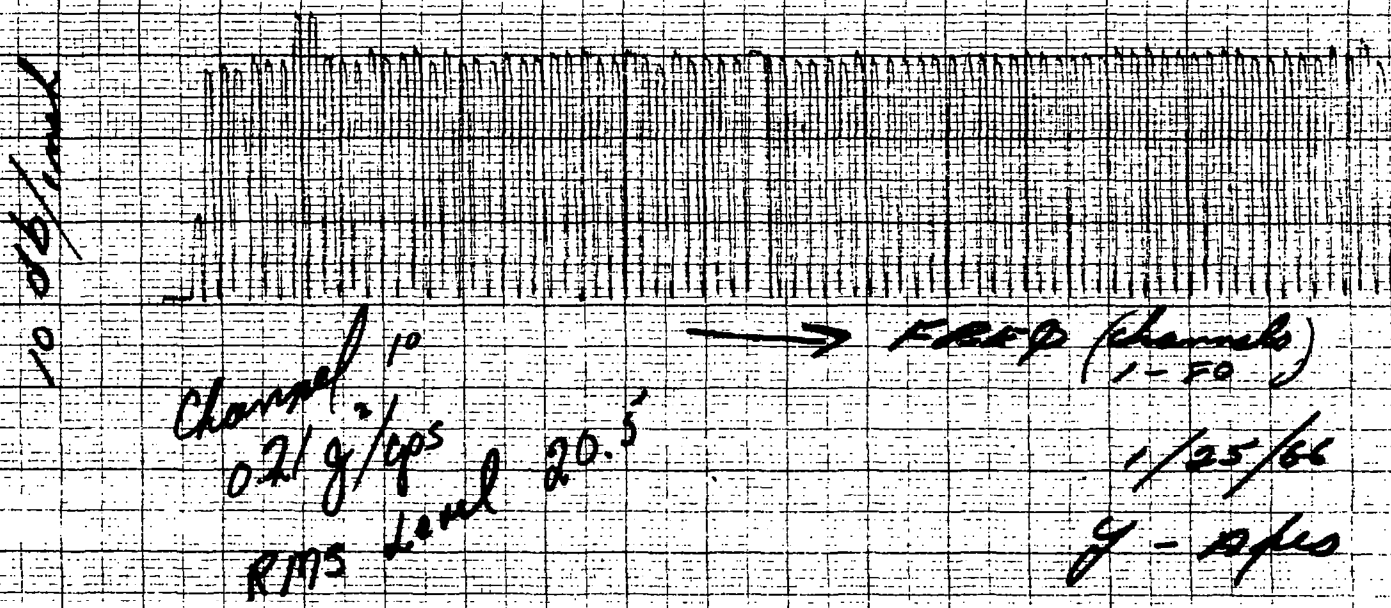


FIGURE I



RANDOM VIBRATION

Y-5660

FIGURE II

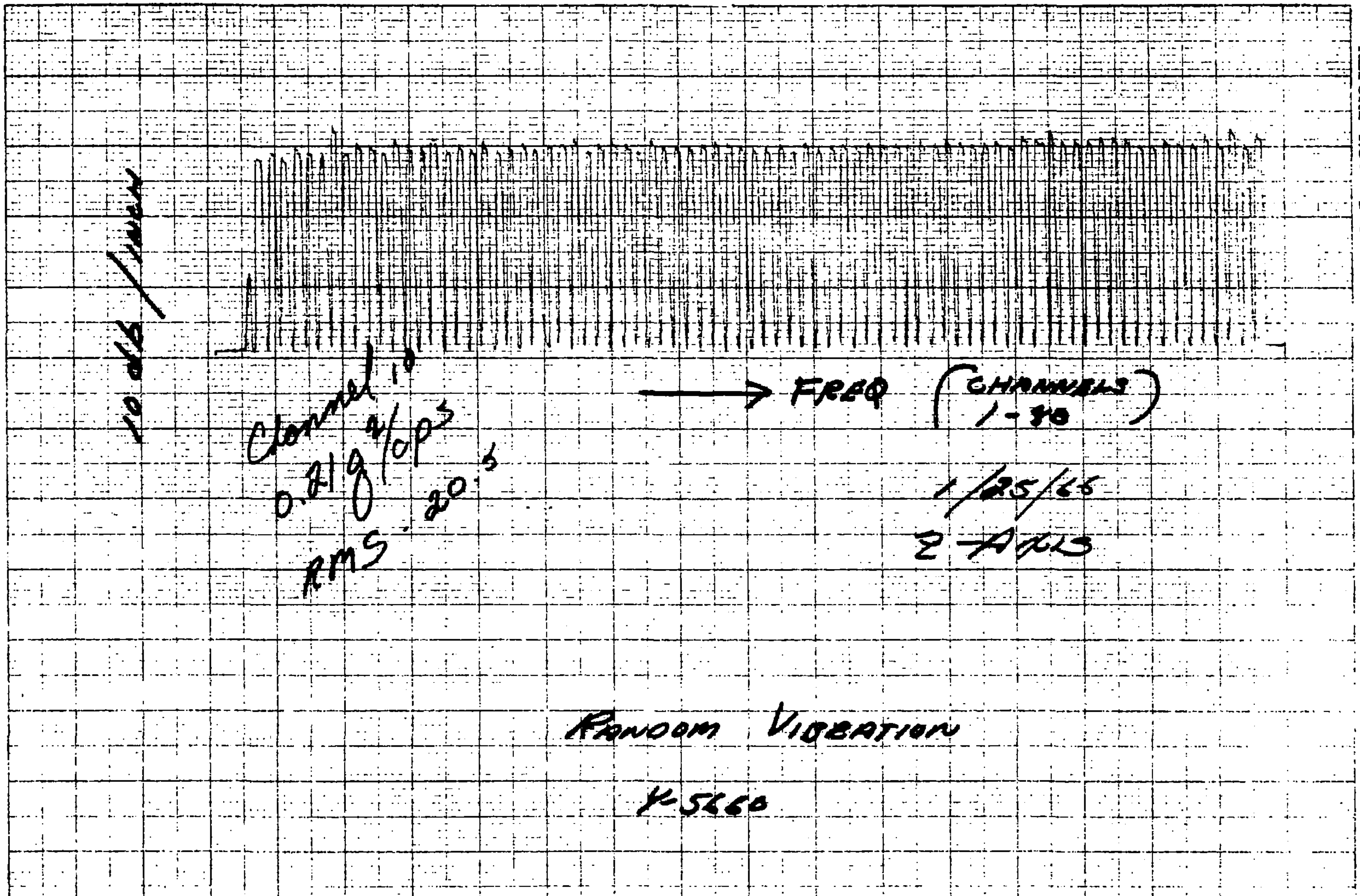

10 db / inch
Channel 10
0.81 g²/cps
RMS
FREQ (CHANNELS 1-80)
1/25/65
Z AXIS
RANDOM VIBRATION
Y-5660

FIGURE III

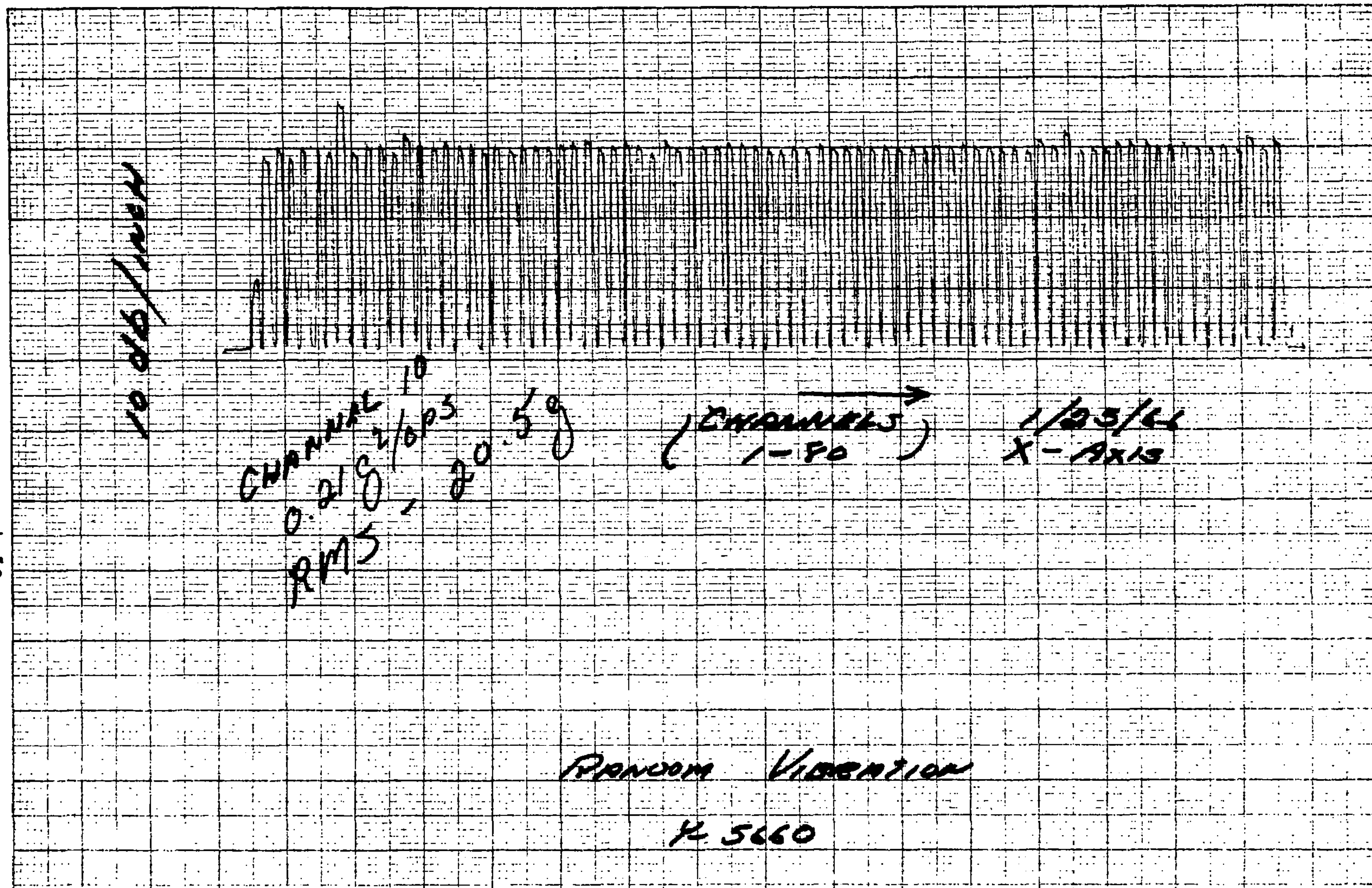

10 db/inch
CHANNEL 10
0.21 g RMS
(CHANNELS 1-80)
1/23/66
X-AXIS
RANDOM VIBRATION
Y-5660

FIGURE IV

CERTIFICATION

Tested Under The Supervision Of

Michael Kiyak
Project Engineer

Certified By

Jeremiah J. McCarthy, Manager
Environmental Testing Division

February 9, 1966

State of Connecticut)
) ss Stamford
County of Fairfield)

Subscribed and sworn to before me this ninth day of February, 1966.

NOTARY PUBLIC

SUMMARY OF VIBRATION TEST RESULTS
AT YORK RESEARCH

Sinusoidal Vibration

X-X Axis Configuration

	Before	After
Side A	λ	λ
Side B	λ	λ

Z-Z Axis Configuration

Side A	λ	λ
Side B	λ	λ

Y-Y Axis Configuration

Side A	λ	λ
Side B	λ	λ

Sustained Acceleration

X-X Axis Configuration

Side A	λ	λ
Side B	λ	λ

Z-Z Axis Configuration

Side A	λ	λ
Side B	λ	λ

Y-Y Axis Configuration

Side A	λ	λ
Side B	λ	λ

Random Vibration

Y-Y Axis Configuration

	Before	After
Side A	λ	λ
Side B	λ	λ

Z-Z Axis Configuration

	Before	After
Side A	λ	λ
Side B	λ	λ

X-X Axis Configuration

	Before	After
Side A	λ	∞*
Side B	λ	∞*

*Failure was determined as resulting from secondary vibrations in the test fixture rather than a structural deficiency in the beamsplitter mount.