# ALMA Memo #269

# Tests of Materials for Use in Multi-Layer Infrared Filters in Cryogenic Application

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## Abstract

Thermal loading of cryogenic receivers is often dominated by infrared radiation accompanying the desired signal. This loading can be minimized by low-pass filters in the signal path. Here the use of multiple layers of thermally isolated materials is investigated for this purpose. Measurements of several materials are reported and compared with calculations.

Key Words: cryogenics, receivers, infrared filters

## Introduction

Most earlier work on infrared filters for millimeter and submillimeter wavelength receivers has involved the use of relatively thick layers of absorbing material that are cooled to a temperature between ambient and that of the receiver [1] [2]. There are two difficulties with this: First, the intercepted radiation loads the intermediate stage refrigerator. Although this is not as burdensome as loading the lower-temperature receiver, it is still significant. And second, the desired properties of the materials for this purpose, namely high transparency to mm wavelengths and high thermal conductivity, tend to be mutually exclusive. Accordingly, we investigate here the use of thermally isolated filters. A set of $N$ isolated layers, each of which is thin but fully absorbing at IR wavelengths, will reduce the transmitted IR radiation by a factor of $1/(N+1)$. The energy not transmitted is re-radiated through the input, imposing no load on the refrigerator. However, practical materials that are transparent to longer wavelengths are not fully absorbing at IR. In this memo, measurements of the IR properties of several practical materials are reported and analyzed.

## Experimental Set-Up

Figure 1 shows the set-up used for these experiments. A three stage Gifford-MacMahon and JT cooling system was used to bring a stage to 4K temperature. The stages also provided cooling to radiation shields at 50K and 4K temperatures. An aluminum alloy spacer was placed between the 4K stage and a copper plate, here called the “IR stage.” Calibrated temperature sensors were mounted at the IR stage and the 4K stage. A heating element was placed at the IR stage.

All parts of the 4K and IR stages are shielded by 4K and 50K radiation shields. Openings were made in these shields to allow the IR stage to be illuminated by a room temperature brass plate. The brass plate, IR stage, and all inside surfaces of the radiation shields were coated with

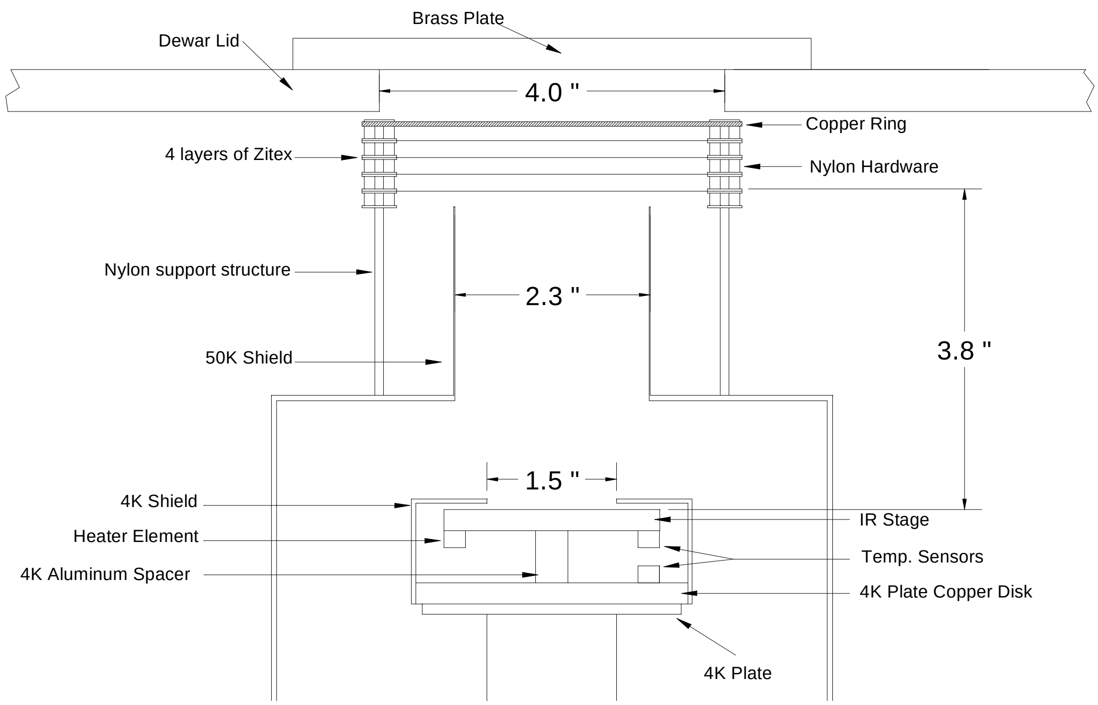


Figure 1. Experimental Setup for
Floating IR Shield Test

black soot from a smokey flame to increase their emissivity. In all other directions, the system was shielded by either high emissivity cold surfaces or low emissivity floating shields. Radiation from sources other than the brass plate was negligible.

## Filter Materials

The filter materials were chosen based on availability and anecdotal information from other users of these materials. The goal of investigating multi-layer filters drove the need for thin sections of the materials. This also limited the choice of materials. The RF properties of these materials are well known for some.  However, the electrical properties may not be known for similar RF bands of operation.  Where the RF properties are known, they are written here. References are made to work where the electrical properties are reviewed or tested.  The materials tested were:

Zitex G115.  A 0.015" thick, expanded PTFE material, produced as a biological liquid filter element.  It is made in a patented process which produces a 50% void and is guaranteed to be homogenous.  It has a refractive index of 1.22 ($\epsilon_r$=1.5)  and a loss tangent of 0.00022 at 10 GHz. Zitex  is produced by Norton Performance Plastics of Wayne, New Jersey.

Arco Dylite Expanded Polystyrene.  A 0.4" thick, polystyrene foam material, of 1.22 lb/ft$^3$ density, used as backing material in some NRAO receiver dewar windows.  Some RF properties of this material have been characterized by Kerr [3].  The Dylite material is supplied by the Radva Corporation of Radford, Virginia.

Gore-Tex RA-7957.  A 0.13" thick, expanded PTFE material, which is commonly used in radomes.  It has a refractive index of 1.1 ($\epsilon_r$=1.21).  The refractive index and power absorption coefficient were measured by Paine [4] over the submillimeter band.  The Gore-Tex material is supplied by W. L. Gore & Associates of Elkton, Maryland.

## Procedure and System Calibration

The temperature of the 4K stage was maintained at 3.97K  ±0.03K for all of the experiments.  Also, the IR stage-spacer-4K stage system was never disturbed during the testing period.  In this manner, a specific temperature difference across the aluminum spacer could be directly related to an amount of heat at the IR stage.  To calibrate the system, measurements were made with the 50K shield opening covered by a brass plate.  Power was incrementally applied to the heater element at the IR stage and the temperatures of the 4K and IR stage were measured. This data provided a measure of the thermal conductivity of the aluminum spacer and the residual power at the IR stage.  Similar measurements were made with the shield apertures open to the room temperature load.  These measurements provided a value of the power from the room temperature load to the IR stage.  Figure 2 shows the results of the first and the final calibration measurements.  The first calibration test was made before the filter tests began and the final calibration measurement was made at the end of the experiment.  This data confirms that the test system remained constant throughout the filter tests.

Multi-layer infrared filters were constructed and placed between the 50K shield opening and the room temperature load.  The filter support structure consisted of 8, #6 nylon screws and a copper ring.  The copper ring was drilled to take the 8 nylon screws and used to provide stiffness to the structure.  The filter layers were isolated from the copper ring and each other by 0.2" thick nylon nuts and thin nylon washers.  This provided spacings of approximately 0.25" between the filter layers.  Measurements of the heat load at the IR stage were made using filters with 1 to 4 layers of material.  This data was analyzed and compared to ideal filter calculations.

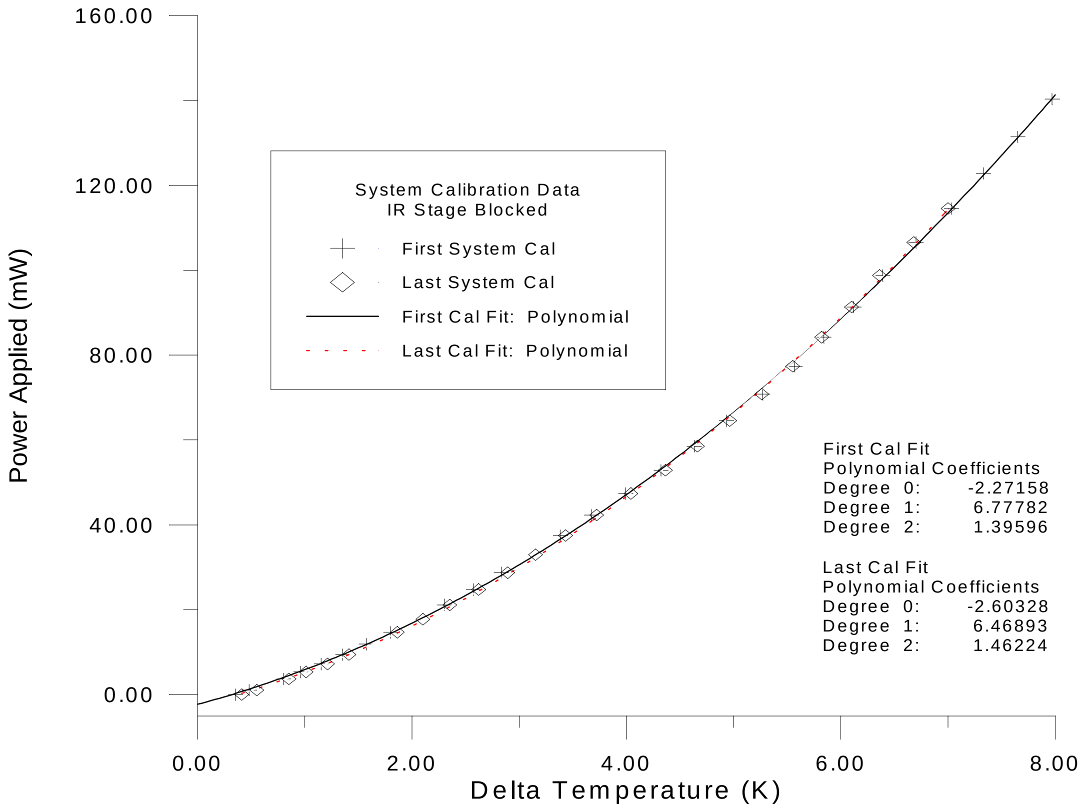


Figure 2. First and Last System Calibration

## IR Transmission Data and Analysis

The results of the filter tests are shown in Figure 3. Power absorbed on the IR stage is plotted as a function of the number of layers of filter material. The Zitex measurements were performed twice (separate cooldowns) at each number of layers. The Zitex measurements and their averages are plotted. The other materials were measured only once.

With no filter, the power absorbed by the IR stage was $P_0$ = 67.5 and 69.8 mW on separate cooldowns before and after the experiment, respectively. This compares with a calculated power of:

$$P_0 = \alpha_h \alpha_c (140\text{mW}) \tag{1}$$

where $\alpha_h$ is the emissivity of the hot brass plate and $\alpha_c$ is that of the cold IR stage. The calculation involved numerically integrating the radiation across the aperture, neglecting any contributions from the shields. (As shown in Figure 2, residual radiation from the shields, or other leakage sources, was very small.) We can reliably estimate that $\alpha_h$ is approximately 0.95, but emissivities at low temperatures are not well known [5]. From this measurement, we estimate that the soot covered IR stage had $\alpha_c$ of approximately 0.52. This value does not affect the following results, provided it remained constant throughout the experiments.

Now consider the results for single-layer filters. If the material is thermally isolated except for radiation, and if the upper surface sees only temperature $T_h$ and the lower surface sees only temperature $T_c$, then in thermal equilibrium, it will be at temperature $T_1$ given by:

$$T_h^4 + T_c^4 - 2T_1^4 = 0 \tag{2}$$

provided that it is thin enough that it's temperature is constant. For the thicker materials, we can regard $T_1$ as an effective temperature. If the material has absorptivity (emissivity) $\alpha$, reflectivity zero, and hence transmission (1-$\alpha$), then the power absorbed at the cold stage is:

$$P = g\sigma[(1-\alpha)T_h^4 + \alpha T_1^4] \tag{3}$$

where $g$ is an effective area that depends on the system geometry and $\sigma$ is the Stefan-Boltzman constant. Since $P_0 = g\sigma\, T_h^4$, we have:

$$\frac{P}{P_0} = (1-\alpha) + \alpha\frac{T_1^4}{T_h^4} \tag{4}$$

Using (1) and (4), and taking $T_c << T_{h,}$ then gives:

$$\alpha = 2\left(1 - \frac{P}{P_0}\right) \tag{5}$$

From (5) and the measurements, we deduce the absorptivities given in Table 1 for a single layer of each of the materials. Assuming that transmission decreases exponentially with thickness, Table 1 also gives the calculated absorption coefficient per unit thickness.

For multiple layers, a similar, but algebraically complicated analysis yields predicted

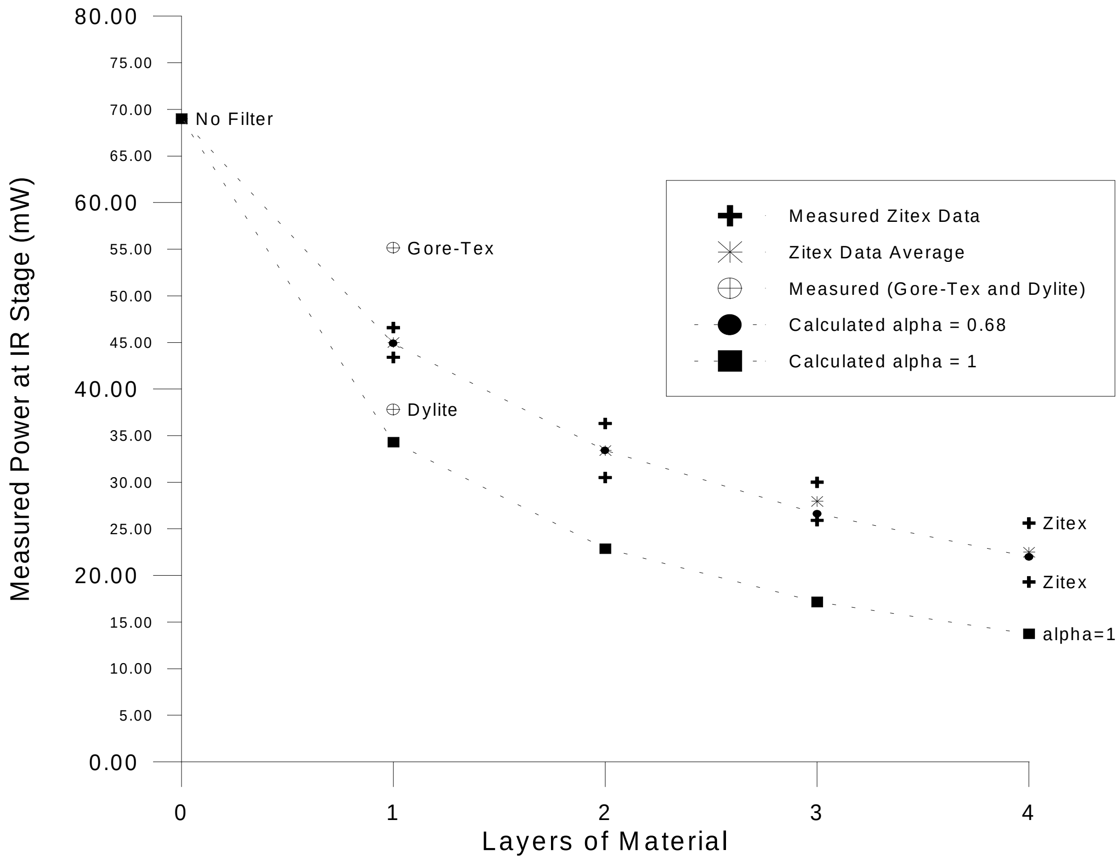


Figure 3. Test Results

values of the temperature of each layer and the transmitted power. The calculation is shown in appendix 1 as a MathCad [6] worksheet. Using the Zitex absorptivity of 0.68 derived from the 1 layer measurement, the predicted powers for 2, 3, and 4 layers are plotted in Figure 3. The derived values show good agreement with the measurements.

Table 1
Summary of Single Layer Results

| Material | Sample Thickness (mm) | 1-Layer Transmission ($t$) | Effective Emissivity ($\alpha$) | Effective Abs. Coef. ($mm^{-1}$) |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Zitex | 0.318 | 0.66 | 0.68 | 3.66 |
| Dylite | 10.1 | 0.55 | 0.91 | 0.23 |
| Gore-Tex | 3.3 | 0.80 | 0.40 | 0.15 |

## Discussion

These experiments and this analysis were focused on the IR properties of various materials and layered configurations of the materials as filters for use in millimeter and submillimeter wave receivers. While the Zitex material shows a high absorption in the infrared, it also has a comparatively high dielectric constant. Thick, solid materials allow for the machining of grooves to provide a matching interface between the material and the vacuum space. The use of the thin layers of material would not allow for this matching surface machining. These factors may reduce the relative efficacy of thin multiple layers as opposed to optically thick IR filters. However, the experimental data presented here shows that only two layers of the thin Zitex material provides the infrared absorption of a single layer of the Dylite sample. A single Zitex layer is more IR absorptive than a single Gore-Tex layer almost ten times its thickness. Clearly, the testing of multiple layer IR filters in the RF bands of interest is recommended. Once the RF characteristics of these filters are tested and understood, the value of further IR testing can be determined.

While we are confident the experimental set-up was stable throughout the experiments, the considerable time and resources required for each trial limited the number of repetitions possible for each experiment. This severely limits the ability to derive statistical error values. Because the filter materials tested were of different thicknesses, the analysis carried out for multiple thin layers may not be valid for thicker layers of material. There is likely to exist a temperature gradient across a thick filter layer. As mentioned in the analysis section, an effective temperature was used for the temperature of the thick filter layers. There may be errors introduced in the results by the application of the same analysis for the thin and thick filter layers. We believe that the effective temperature, used in the thick layer analysis, is a valid approach and allows comparisons of the materials as IR absorbers.

## Conclusions

Multi-layer, thermally isolated IR filters can be constructed of thin, absorptive materials. PTFE materials have been successfully used in optically thick, cooled filters. The thin layers of PTFE materials, needed to produce these multi-layer filters, are now readily available. Because these filters are floating and do not need to be thermally terminated on a cold stage, they may substantially reduce the load capacity requirements of all the stages of the refrigeration systems used in cryogenic receivers. The RF performance of these multi-layer IR filters should be tested in the frequency bands of interest.

## References


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[2] J. Ibruegger: "Transmission of Room-Temperature Radiation by Materials at Low Temperatures", *Int. J. IR and Millimeter Waves*, Vol. 5, No. 5, 1984.

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[4] S. Paine: Report of FTS test results for Gore-Tex RA-7957, Letter to A. Kerr., Smithsonian Astrophysical Observatory, Oct 24, 1995.

[5] T. Flynn: *Cryogenic Engineering*, Marcel Dekker Inc., 1997, Table 5.8, p. 247.

[6] MathCad 8: Mathematics calculation program. MathSoft Inc. Cambrige, MA., 1991-1999

Appendix 1

# Multi-Layer Filter Analysis

We have N identical layers of partially-absorbing material between two black bodies, and we wish to find the flux that is transmitted from the hot body to the cold one.

Each layer absorbs a fraction *a* of the radiation incident on it and transmits fraction (1-*a*). Reflection is neglected.

$N := 4 \qquad a := .69$ Number of layers; absorption of each.

$T_c := 4 \qquad T_h := 300$ Temperatures of cold and hot black bodies.

$f(i,j) := a \cdot (1-a)^{|i-j|-1}$ Set up matrix equation.

$A := matrix(N+2, N+2, f)$

$k := 1 .. N \qquad A_{k,k} := -2$

$k := 1 .. N+1 \qquad A_{0,k} := 0 \qquad A_{N+1,k-1} := 0 \qquad A_{0,0} := 1 \qquad A_{N+1,N+1} := 1$

$B_{N+1} := \frac{T_c^{\,4}}{a}$

$B_0 := \frac{T_h^{\,4}}{a}$

Effective temp^4 at hot and cold sinks, as if they have emissivity a like the filter layers. This trick makes the equations more symmetrical.

$p_N := \left(A^{-1}\right) \cdot B$

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0.69 & -2 & 0.69 & 0.214 & 0.066 & 0.021 \\ 0.214 & 0.69 & -2 & 0.69 & 0.214 & 0.066 \\ 0.066 & 0.214 & 0.69 & -2 & 0.69 & 0.214 \\ 0.021 & 0.066 & 0.214 & 0.69 & -2 & 0.69 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Temperatures of layers:

$$\overrightarrow{p_N^{\,.25}} = \begin{bmatrix} 329.161 \\ 279.581 \\ 262.341 \\ 240.821 \\ 211.214 \\ 4.389 \end{bmatrix}$$

pseudo
true
true
true
true
pseudo

$$fracN := \left[ \sum_{i=0}^{N} (1-a)^{N-i} \cdot \frac{p_{N_i}}{p_{N_0}} \right]$$

Fraction absorbed on cold stage

$fracN = 0.322$