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# INFRARED FILTERS FOR CRYOGENIC RECEIVERS

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## 1 Introduction

To reduce the heat loading on the 4 K station of the receiver and to keep the temperatures of the cooled receiver components as low as possible the infrared radiation from ambient needs to be blocked. This may be done using a filter which is transparent to millimeterwaves but opaque to infrared. The material from which the windows are made should have a low dielectric constant and absorption at millimeter wavelengths to minimize reflective and dissipative losses. In the infrared it should be highly absorptive to minimize transmission of heat. For the material to emit a minimal amount of radiation to the cold station it should be at a low temperature, which implies that the thermal conductivity should be high so that the center of the filter is not significantly warmed by the radiation incident from ambient. In the dewars used for the NRAO millimeterwave receivers the IR windows are relatively large (76 mm in diameter) so that the temperature uniformity is an important issue. This note describes the selection procedures for materials, the thermal design of the filter and some experimental results of heat load tests.

## 2 Selection of Material

Ibruegger [1] has investigated the transmission of room temperature infrared radiation by several materials. The materials which best block the IR are PTFE, Stycast HiK, fused quartz, crystalline quartz and Fluorogold. Table I gives the millimeterwave properties of some suitable materials. Stycast HiK and quartz both have relatively high dielectric constants which makes impedance matching at millimeterwave frequencies more difficult over a reasonable bandwidth. Fluorogold has a somewhat higher refractive index than PTFE but is birefringent [2] (as is crystalline quartz). Fluorosint, a PTFE based material similar to Fluorogold [3], does not suffer from birefringence but has a higher refractive index and higher absorption than PTFE [3]. Measurements

| Material | Refractive Index | Loss tangent | (Frequency) |
|---|---|---|---|
| Fluorogold | 1.62 (parallel to grain) | $6 \times 10^{-3}$ | (300 GHz) |
| | 1.60 (perpendicular to grain) | $4 \times 10^{-3}$ | (300 GHz) |
| Fluorosint | 1.87 | $5 \times 10^{-3}$ | (300 GHz) |
| PTFE | 1.44 | $2 \times 10^{-4}$ | (90 GHz) |
| Quartz, crystalline | 2.11 (ordinary) | $8 \times 10^{-4}$ | (900 GHz) |
| | 2.16 (extra ordinary) | $5 \times 10^{-3}$ | (600 GHz) |
| Quartz, fused | 1.95 | $3 \times 10^{-3}$ | (600 GHz) |
| Stycast HiK | 2 | - | |

**Table I** Optical properties of potential IR filter materials at the closest frequencies to 300 GHz available.

by Birch *et al.* [4] show that PTFE has very good transmission in the millimeterwave spectrum, but a strong absorption band starts at a wavelength of about 60 μm [5]. The low loss and relatively low dielectric constant of PTFE make it the best choice as far as signal transmission is concerned. Although its IR transmittance is higher than Fluorogold or Fluorosint, the thickness of the window is determined more by the need to have a low thermal resistance than by the IR transmission — when the window is thick enough to conduct the incident heat away the transmitted radiation is small, as will be seen in the next section.

PTFE and the related materials Fluorogold and Fluorosint are not brittle, even at low temperatures, and there is therefore no danger of breakage on cooling. Using materials such as quartz would require careful design for these large filters to avoid excessive stress on the material which is relatively brittle.

## 3 Thermal Load Calculations

Some simple calculations of the expected heat load through the windows were made to assess the effects of various design parameters. Figure 1 shows the geometry assumed in the analysis. There is a flux, $q_0$, incident on the filter from the vacuum window, which is assumed to be black body radiation emitted at a temperature $T_0$, given by

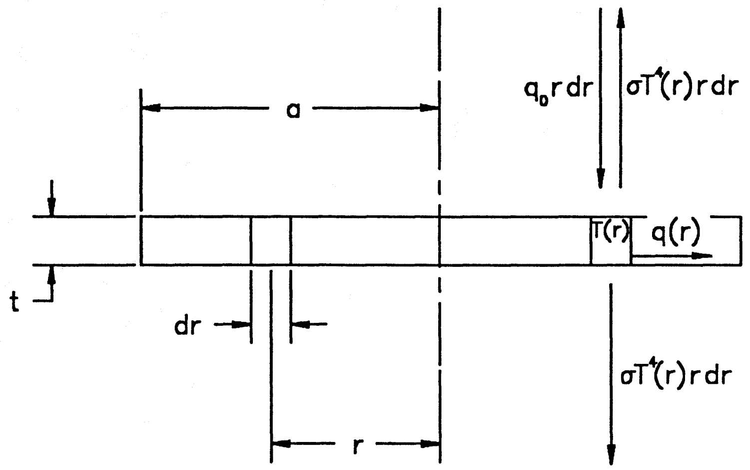

**Figure 1** Geometry assumed in calculations. The equations are written for an annulus of width *dr* at a radius *r*.

$$q_0 = \sigma T_0^4 \tag{1}$$

where $\sigma$ is Stephan's constant. If the refractive index of the window material is $n$ then a fraction $\rho$ is reflected from the front surface, where

$$\rho = \left(\frac{n-1}{n+1}\right)^2 \tag{2}$$

Of the radiation which is not reflected, a fraction $\alpha$ will be absorbed, depending on the thickness $t$:

$$\alpha = \exp\left(-\frac{t}{t_0}\right) \tag{3}$$

$t_0$ is the thickness required to attenuate the power by 1/e. The power absorbed per unit area at the window is therefore

$$q_0' = \alpha(1-\rho)q_0 \tag{4}$$

The circular symmetry of the geometry allows the energy balance to be expressed in one dimension. If the temperature profile as a function of radius is $T(r)$ and the total heat flowing radially through the material is $q(r)$, then the temperature drop across an annulus of thickness $dr$ at a radius $r$ is given by

$$dT = \frac{q}{k(T)}\frac{dr}{2\pi rt} \tag{5}$$

$k(T)$ is the thermal conductivity of the material at a temperature $T$. The net heat influx to the annulus is the difference between the black body radiation from the room temperature side and the black body radiation to ambient and the 4 K station. Hence

$$dq = \left[q_0' - 2\sigma T^4\right]\pi r dr \tag{6}$$

the factor of two arising because of the two surfaces. Note that the radiation from the 4 K station is negligible. Equations (5) and (6) cannot generally be integrated in closed form, but some simplifying assumptions give an approximate result. Assume that the thermal conductivity is independent of temperature, and assume that the second term in equation (6) is small compared to the first (which will be reasonable for a very good filter since the temperature of the filter should be much less than ambient). If the temperature at the edge of the filter is $T_e$ then integration gives a parabolic temperature profile for the filter

$$T(r) = T_e + \frac{q_0'}{4kt}(a^2 - r^2) \tag{7}$$

The temperature profile may be integrated to give the emitted heat load on the 4 K station

$$P_e = \epsilon\sigma\int_0^a T(r)^4 r\,dr \tag{8}$$

A closed form expression can be obtained when (7) is substituted in (8)

$$P_e = \frac{a^2}{10}\left(x^4a^8+5x^3a^6T_s+10x^2a^4T_s^2+5T_s^4\right) \tag{9}$$

where

$$x = \frac{q_0'}{4kt} \tag{10}$$

Note the very strong dependence on the filter radius ($a^{10}$). If (5) and (6) are integrated numerically, then (8) also has to be evaluated numerically.

The transmitted power

$$P_t = (1-2r)(1-a)q_0 \tag{11}$$

must be added to the emitted power to give the total heat load on the 4 K station

$$P_{tot} = P_e + P_t \tag{12}$$

Equation (12) has been evaluated for PTFE filters of various thicknesses using both the numerical and analytical temperature profiles using published values for the thermal conductivity of PTFE [6]. The

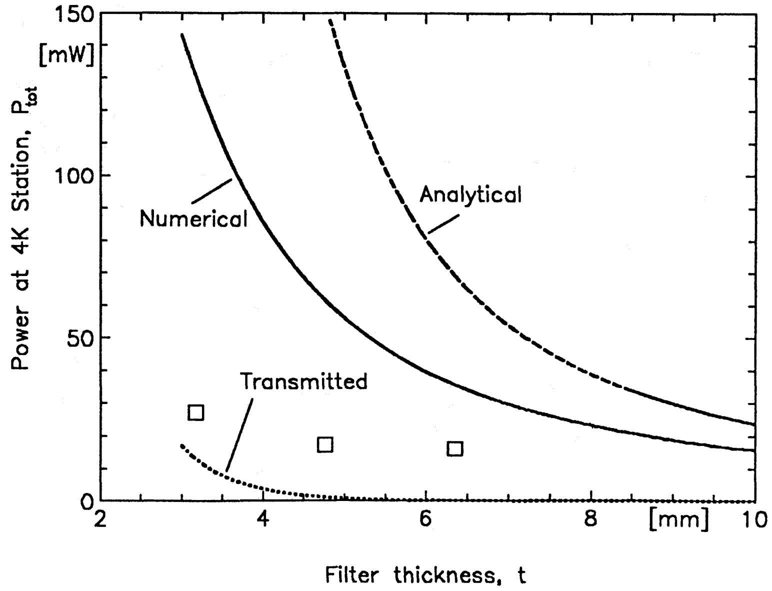

**Figure 2** Calculated and measured power delivered to the 4 K station from an IR window made from PTFE. The points are measured data. Parameters are given in the text.

results shown in Figure 2 assume that the filter has a radius $a = 38$ mm and sees an ambient temperature $T_0 = 295$ K, The edge of the filter is at $T_e = 51$ K (the temperature of the filter holder in the experiments). The analytical results are larger than the numerical ones, since the power re-radiated by the window is neglected. The transmitted power is also plotted and it can be seen that it is negligible compared to the emitted power.

## 4 Measurements

Some experiments were carried out to measure the heat load on the 4 K station for several different filters. As shown in Figure 3, a copper plate covered with black paper was attached to the 4 K station of a JT refrigerator with a brass bracket having a thermal conductivity of approximately 5 mW $K^{-1}$. The plate had a temperature sensor and a 300 Ω resistor mounted on it. Different filters were mounted in the filter holder and the temperature of the copper plate was measured for several values of power dissipation in the resistor. This procedure was also used with a blank copper plate in the filter holder, and with a blank copper plate covered with black paper in the holder. The results are shown in Figure 4 for three PTFE filters and one high density polyethylene (HDPE) one. All of the curves have the same shape but are displaced parallel to the power axis. The amount of displacement relative to the curve for the blank copper represents the additional heat load due to radiation from and through the relevant window. The resultant values are given in Table II.

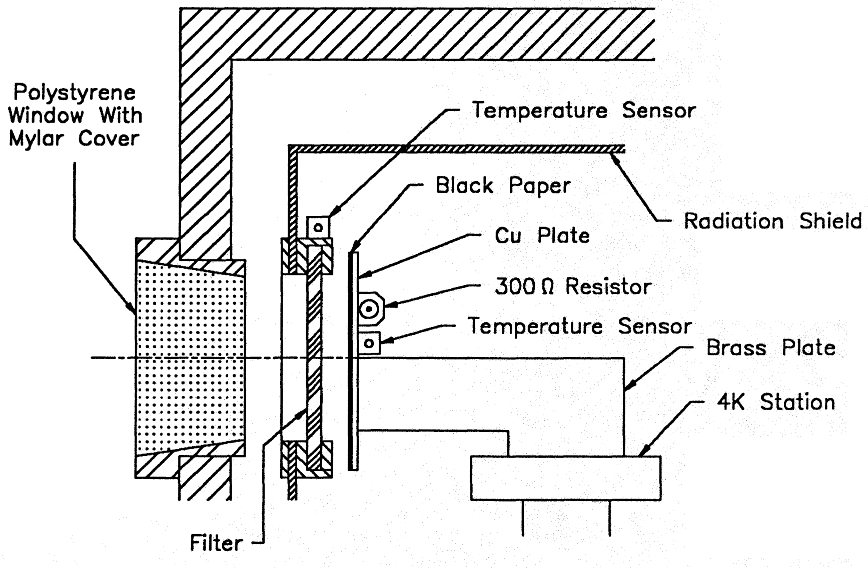

**Figure 3** Setup used for the measurements. The 4 K station is cooled by a JT refrigerator and the shield is attached to the first stage which was at about 51 K.

The measurement with the copper plate with paper in the filter holder should be equal to

$$P = \pi a^2 \frac{\epsilon_p}{2-\epsilon_p} \sigma T_s^4 \tag{13}$$

| Material | Thickness (mm) | Heat Load on 4 K Station (mW) |
|---|---|---|
| Copper Blank | - | 0 |
| Copper with black paper | - | 1.35±0.3 |
| PTFE | 3.18 | 27.4±0.6 |
| PTFE | 4.76 | 17.3±0.7 |
| PTFE | 6.35 | 15.9±0.7 |
| HDPE | 6.35 | 74.6±0.2 |

**Table II** Measured heat loads at 4 K station for different filters.

where $\epsilon_p$ is the emissivity of the paper (assumed to be the same on the two surfaces) and $T_s$ is the temperature of the shield. If it is assumed that the emissivity is unity then this gives a load of 1.6 mW, compared to the measured value of 1.3±0.3. In principle this number may be substituted into (13) to derive an estimate of the emissivity, but in practice the measurement uncertainty does not allow an accurate calibration and the emissivity is assumed to be 0.95 in these calculations [1]. It seems likely that the emissivity of the receiver insert will not be worse than the paper so the measurements of heat loading at least give an upper limit to the magnitude in the receiver.

The measured loads for three thicknesses of PTFE filter are shown in Figure 2 along with the calculated values. Clearly the analytical values are much too high, but surprisingly the numerical results were also significantly higher than the measured ones. The conductivity of PTFE would have to be four times higher than published values to explain this, which is unlikely.

Some further measurements were made by mounting two temperature sensors on the filters, one near the center and the other near the edge. The temperature at the center of the filter was much lower than expected while the temperature at the edge was much larger Table III. Poor thermal contact between the PTFE and the filter holder explains the high edge temperature, but not the low center temperature. It was hypothesized that the results could be explained if it was assumed that the inside of the polystyrene foam window is radiatively cooled to a temperature on the order of 200 K. Two measurements were made to confirm this. Firstly, indirect evidence was obtained by covering the inside of the vacuum window with copper plate covered by black paper, which caused a significant increase in the window temperature. Secondly, a small temperature sensor was embedded in the foam window and a temperature of 230 K was measured, in reasonable agreement with

| Filter | Center Temperature (K) | Edge Temperature (K) |
|---|---|---|
| 6.35 mm Thick PTFE | 104 | 82 |
| 3.18 mm Thick PTFE | 111 | 88 |

**Table III** Temperatures measured on windows. The "edge" temperature was actually about 6 mm from the edge.

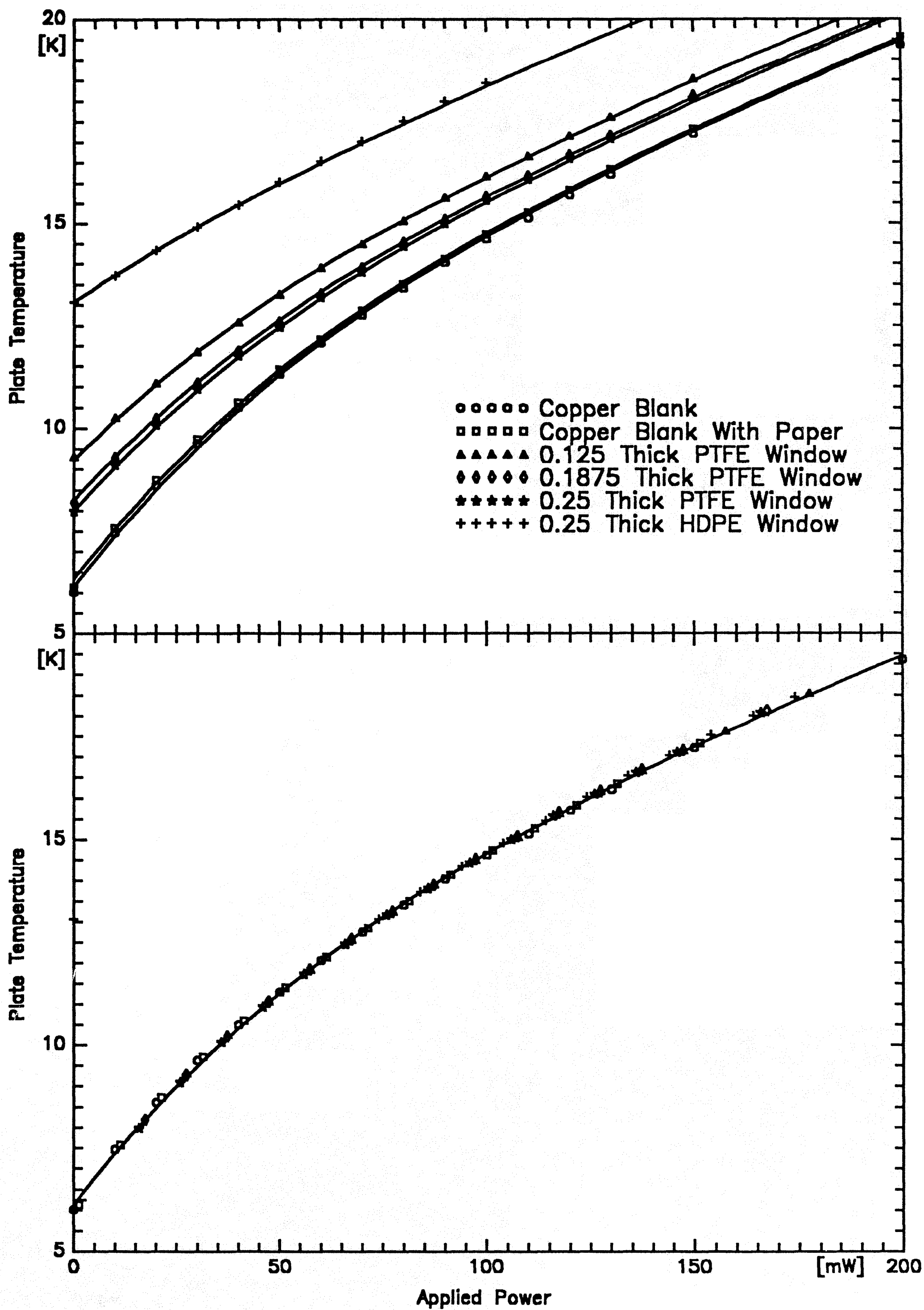

**Figure 4** Temperatures measured on the copper plate for various filters. Upper curves show the measured points, lower one shows the curves moved horizontally to match the one for the blank plate.

expectations.

The HDPE filter was very poor at reducing the heat load because of its high transparency in the IR [7].

## 5 Conclusions

For large IR filters the thermal properties are at least as important as the IR transmissivity. The need to conduct heat away requires a thicker filter than would be dictated by the thickness to make the filter opaque. PTFE is a suitable material because of its low dielectric constant, low loss at millimeter wavelengths, high absorption in the IR and mechanical ruggedness. In the current design the thermal contact between the filter and its holder is rather poor. Fortuitously, the vacuum window acts as a reasonable IR filter since its low thermal conductivity means that it can become quite cold on the inside surface and its blackbody radiated power is correspondingly smaller.

## 6 References

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