Cooling the ATA PLP Feed in the Vacuum Dewar

Jack Welch and Matt Fleming

Summary

It is practical to cool the entire ATA PLP feed in a dewar to a temperature of the order of 70K with a modest refrigerator connected just to its large end. The thermal conductivity of both the pyramid and the feed arms is adequate to maintain a small temperature difference between the feed tip and the refrigerator in the presence of the 300 Kelvin infrared environment. The total infrared thermal load on the refrigerator is estimated to be about 2.5 watts.

Introduction

In an earlier memo, we proposed to use small capacitors made from AlN in the input matching circuit to transfer heat between the feed arms and the pyramid. While this material has high enough thermal conductivity to transfer the heat, its dielectric properties are highly dispersive and not suitable to serve as a high frequency capacitor. Here we investigate heat transfer along the pyramid and feed arms and find that with reasonable dimensions in the pyramid and feed arm fins heat transfer along the feed is adequate to maintain a small temperature drop between the feed and the refrigerator connected to the back end of the feed.

We consider the pyramid and the feed arms separately.

I. The pyramid. Figure 1 shows one face of the pyramid. The heat flow will be the same for all four of its faces. The pyramid angle is 10 degrees. x=0 is the vanishing point. The tip begins at .674” (1.712 cm) and is .118” (.300 cm) wide. The big end is at x= 21.973” (55.81cm). The half width of the pyramid face at a point x is y = ax, where a = .0875 radians. The pyramid is made of high thermal conductivity copper with a clean surface.

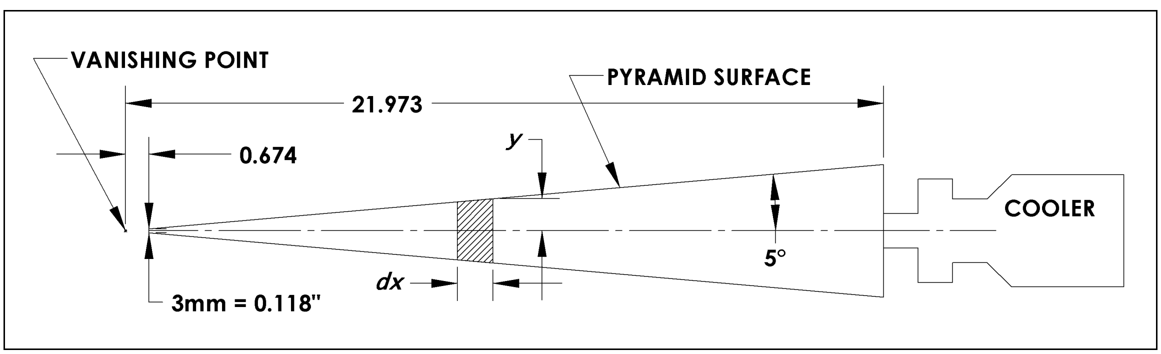

Figure 1 -

The distribution of the infra red flux incident on the pyramid is complicated by the presence of the feed arms above it. A detailed calculation of the flux strength is not simple because the high reflectivity of the copper on both the pyramid and the feed arms implies many bounces of the radiation before it is absorbed. Because of the many bounces, it could be close to the incident value of 300 Kelvin, and we simplify the discussion by assuming it to be exactly the 300 Kelvin, even though it may be somewhat less. $H_0 = \sigma T^4 = 5.7x10^{-12}(300)^4 = .045$ watts/cm^2. For clean copper, the absorption coefficient is $\varepsilon = .03$, or less with gold plating. The infrared heat absorbed in the strip of length dx and width 2y is $dH = \varepsilon H_0 2 ax dx$. The total heat absorbed for $x < X$, which must be flowing in the positive x direction at $x = X$ toward the cold refrigerator is:

$$H(X) = \int \varepsilon H_0 2 ax dx = \varepsilon H_0 a X^2 \quad (1)$$

Starting the integral at x=0 simplifies the formula and causes only a small error. The total power absorbed by all four faces of the pyramid, which has a surface area of 1074 cm^2, is about 1.7 watts, and this must be taken up by the refrigerator.

The heat flow along the face of the pyramid toward the refrigerator must have an associated temperature gradient, dT/dx, at X.

$$H(X) = k \text{ (cross-section area) } dT/dx = k\, 2aX\, t\, dT/dx \quad (2)$$

t is the thickness. For the range $15cm < x < 55.8cm$, t = 1/8" = .318cm. For $x < 15cm$, the pyramid is essentially solid so that the heat can flow with very little temperature gradient. For $x > 15$ cm, there will be a finite gradient. Equating (1) and (2), we can solve for the temperature gradient:

$dT/dx = - [\varepsilon H_0 X]/ 2kt$. For pure copper, $k = 6.5$ watts/cm k^0 at 70K, and $dT/dx = -.0003x$. The total temperature drop over the outer part of the pyramid.is:

$$\Delta T = -\int (.0003x)\, dx = .00015[(55.8)^2 - (15)^2] = -.5 \text{ K}.$$

There is very little temperature drop between the pyramid tip and the refrigerator.

II. The feed arms. Here there is more temperature drop, because all of the heat must flow along the small fin of the feed arm. Figure 2 is an outline of a feed arm with a cell with one pair of tines. One triangular tine on one side has half the area of the approximately rectangular area that contains it. It is the same for the tine on the other side, and from the figure it is evident that the tines occupy one forth of the area of each cell. Because the 300K infrared radiation is absorbed on both sides, the overall absorbing area is half of the arm area.

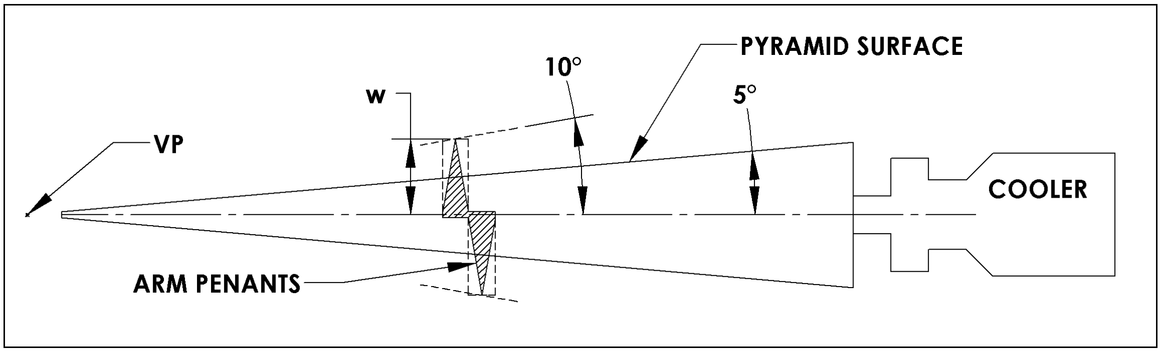

Figure 2 -

The opening angle of the arm is 20^0 as compared with the 10^0 of the pyramid. The width at a point x is w=.349x, for the 20^0 angle. The element of absorbing area is w/2 dx. The element of heat absorbed is $dH=\varepsilon H_0$ .175 x dx, and the total absorbed for x < X is:

$$H(X) = \int \varepsilon H_0 \ .175 \ x \ dx = \varepsilon H_0 (.087)X^2 \quad (3)$$

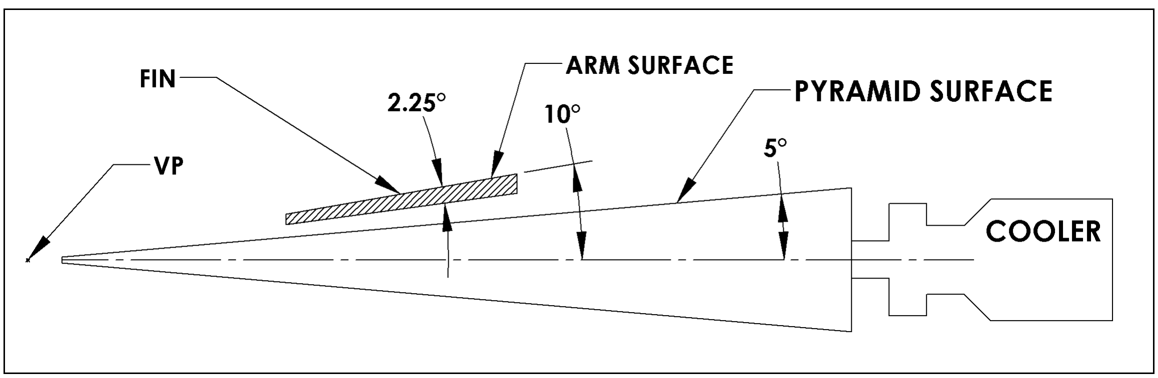

Figure 3 –

Figure 3 is a cross section of the feed showing the position of the arm next to the pyramid. The fin is along the center line of the feed and expands beneath the arm with an angle of 2.25^0. Its thickness is .01"(.0254cm) for the small end which extends up to about 6"(15.24cm). For the longer range out to 55.8 cm, its thickness is .03"(.076cm). The height of the fin with its angle of 2.25^0 is h = .0402x, and, with its thickness of .0254cm in the small region its cross sectional area is A = (.0402x)(.0254). The heat flow at x=X is:

$$H(X) = - k \text{ Area } dT/dx = - k(.001) X \, dT/dx \quad (4)$$

Equating (3) and (4) as before, we find $dT/dx = -\varepsilon H_0 (.087)X/ k(.001) = -(.020)X$. With dT = -.020 x dx, the temperature drop between x= 1.71 cm and 15.24 cm is:

$$\Delta T = \int -.020 \ x \ dx = -.010 \, [(15.24)^2 - (1.71)^2] = -2.29 \text{ K}.$$

For the long section of the feed, the main difference is the fin thickness which is now .030”(.076cm) which reduces the gradient by a factor of three. The total temperature drop in this case is:

$\Delta T = \int -.0066 \, x \, dx = -.0033[\,(55.8)^2 - (15.24)^2\,] = -9.5$ K

Adding to this the -2.3 K from the short section, we get a total of -11.8K temperature drop from the feed tip to the refrigerator. The total area of the feed arms is half that of the pyramid, and the thermal load of the arms is half that of the pyramid, .85 watts. The total thermal load on the refrigerator is about 2.5 watts. The Sunpower Crystal GT cooler will easily have the capacity for this, and the STI Sapphire unit also might work.

The temperature drop along the arms is acceptable, but there appears not to be as much margin as one would like. The assumption that the space between the pyramid and the feed arms is filled with 300K radiation is conservative. More than half of the bounding surface of this region is at about 70K and the remaining surface is at 300K. So the radiation absorbed by the bottom surface of the feed arms may be closer to one half of the amount assumed in the calculation above. In this case, a smaller temperature drop for the feed arms would be expected. We consider the -11.8K calculation as conservative.

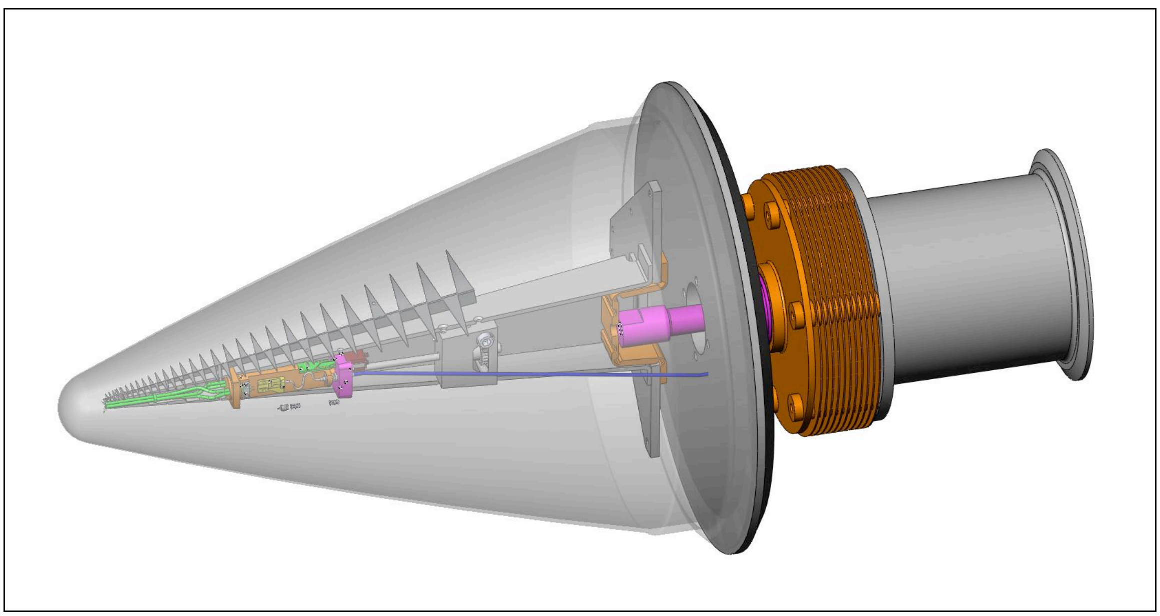

Figure 4- Details of the feed within the dewar. The glass is very thin near the tip and much heavier near the back end. It is largely transparent to the feed radio waves.