Optimizing Source Location For Control of Thickness Uniformity

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ABSTRACT

For a substrate rack in single rotation it is theoretically possible to achieve perfect thickness uniformity simply by developing the correct mask profile for the emission characteristic of the evaporation source. In practice this is quite difficult to accomplish – particularly for large diameter substrates – because the mask will only impose a perfect correction for a unique source characteristic. The source behaviour can vary over time, from run to run and from one material to another. In this paper we show that theoretical modeling can lead to a chamber layout which is less sensitive to such variations in source behaviour and therefore should result in more consistent thickness uniformity

INTRODUCTION

The discussion in this work examines thickness distributions which arise when films are deposited on a flat, rotating plate from an evaporation source offset by ***S*** from the rotation axis. The film thickness, ***t***, is a function of rack radius ***R*** and also depends on the offset, ***S*** (see Figures 1&2). Both ***R*** and ***S*** are expressed as percentages of rack height, ***h***, and in the analyses they are allowed to vary from 0 to 100%.

The resulting thickness distributions depend on both the Chamber Geometry (the rack height, source offset) and the Source Behavior.

The Chamber Geometry is constant, in that once the dimensions have been selected and the chamber set up, their effect on the thickness pattern is always the same.

The Source Behavior is a variable: even if no deliberate changes are made, the way that the source emits will almost certainly vary for a variety of reasons: there may be intrinsic differences between one material and another, or progressive changes in the way a material behaves as it becomes conditioned or depleted during a run, or simply random fluctuations as a result of the way the material is loaded into the source and the subsequent evolution of the evaporant surface. It is these variations which limit our ability to achieve perfect uniformity of thickness across the rack. Theoretically it can be shown that, regardless of how large the range of source behavior is, the resulting non uniformity can be minimized by selecting the best source offset.

BACKGROUND

Many models have been used to describe the way an evaporation source behaves. The source can be considered to emit according to some function, F(φ), of the emission angle, φ , which is the angle between the vapor stream and the normal to the source. F(φ) is sometimes known as the Source Function, or Emission Characteristic of the source.

We favor the expression cos ^{Q} (φ) as a source function[1]. It allows a good fit with data from most sources we have analyzed and it has the merit of simplicity - a source can be described by a single number, the Source ***Q***.

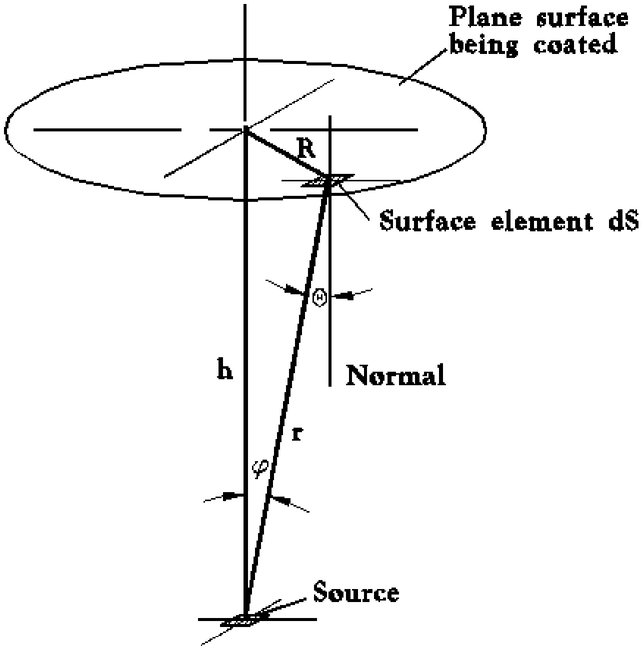

Figure 1: Geometry for a Central Source

In the case of a central source (Figure 1) it can be shown that the relative thickness at any radius (***R***) on the rack is given by

$$t_R / t_0 = \cos^Q(\varphi) \bullet \cos^3(\theta) \qquad (1)$$

Where φ and θ are the emission and deposition angles respectively, as shown in the figure In this case, because the angles φ and θ do not change during the rotation, it is convenient to use the cosine expressions.

In the case where the source is offset from the rotation axis of the rack (Figure 2), the situation is a little more complicated:

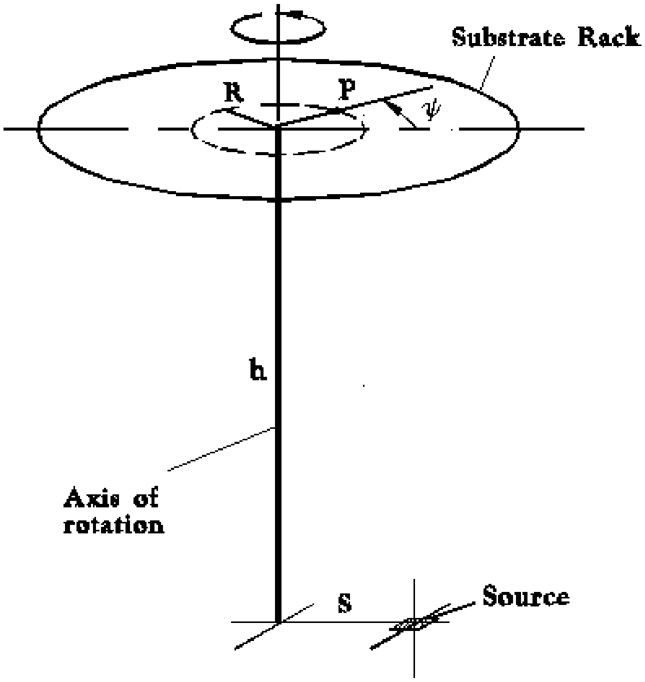

Figure 2: Geometry for an Offset Source

ψ is the Azimuth
R is the Rack Radius
h is the Rack Height
S is the Source Offset

For any point, P, on the rack, the thickness, ***t***, is given by:

$$t \propto \frac{h^Q}{(h^2 + S^2 + R^2 - 2SR\cos\psi)^{Q/2}} \bullet \frac{h}{(h^2 + S^2 + R^2 - 2SR\cos\psi)^{3/2}} \qquad (2)$$

If ***Q*** is made equal to either 0 or 1, equation (2) simplifies to expressions for a point source and a cosine source which are more commonly seen in discussions on the subject.[2] Equations (1) and (2) could be simplified a little further, but they have been left as they are to illustrate that each contains a term which depends on ***Q*** and so relates to the Source Behaviour, and a second term which depends simply on the Chamber Geometry. The equations can be used to calculate thickness distributions, ***t*****(R)** , for different Source Offsets (***S***) and values of Source ***Q***. In this work we used pre-existing computer programs to generate the thickness distributions.

UNIFORMITY LIMIT

Whatever the thickness distribution, it can be corrected by installing and trimming a uniformity mask to a shape which completely evens out the thicknesses[3]. However, the mask can only correct for a unique thickness pattern; if the source characteristic changes, the underlying thickness distribution will change and the uniformity mask will no longer be completely effective. In other words, the range of source behavior imposes a limit on the thickness uniformity which can be achieved.

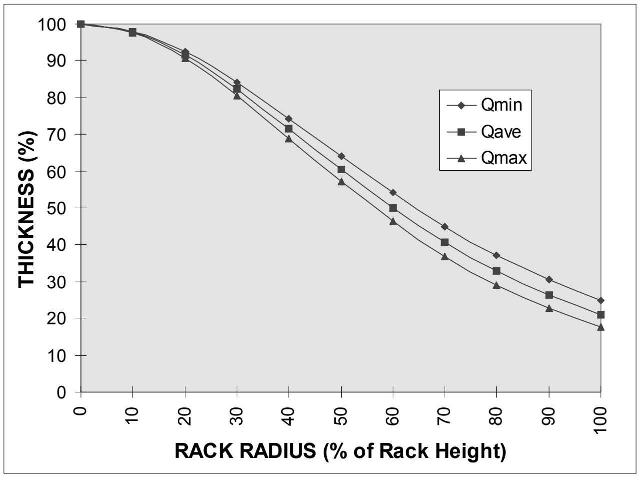

Figure 3:Thickness Distributions for $Q_{\min}=1$, $Q_{\max}=2$ and $Q_{\text{ave}}=1.5$

In Figure 3 we see the case of a central source whose behavior ranges from $Q_{\min}$ to $Q_{\max}$. In practice, a uniformity mask would be designed to correct the distribution corresponding to Q_{ave}, so that when the source behaved with $Q_{\min}$, the correction would be too great, and if it behaved with $Q_{\max}$, the correction would be insufficient. At first glance, this may not appear too serious. Even at the edge of the rack (***R***=100), the difference between $t_{Q\min}$ and $t_{Q\max}$ is only a few percent. However, as a fraction of the total thickness at the edge, the difference is quite large, as can be seen in Figure 4, which shows the resulting thickness distribution after the source in Figure 3 has been subjected to masking designed for $Q_{ave.}$ With this arrangement ($S = 0$, $Q_{min} = 1$ and $Q_{max} = 2$) the effect of the range of source behavior is clearly quite severe: even with the "best" masking there will, at times, be a 17% non-uniformity at the edge of the rack.

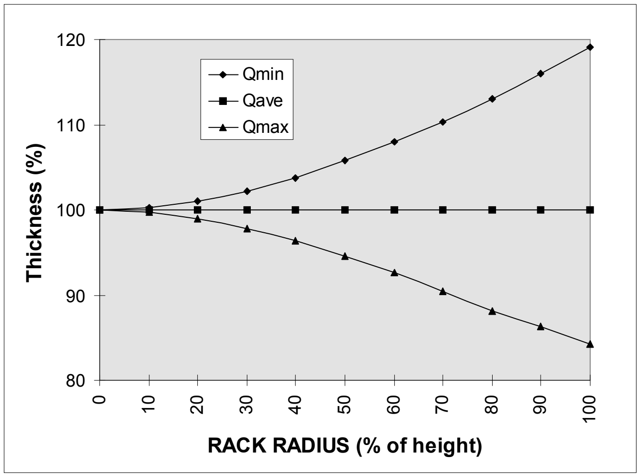

Figure 4: Uniformity Limit after Masking. Central source with Q ranging from 1 to 2

At this point it is useful to introduce a quantity we have called DELTA,(Δ), the normalized difference in thickness between a Q_{min} source and a Q_{max} source. DELTA,(Δ) is a function of rack radius ,R:

$$\Delta(R) = 100 \bullet \frac{t(R)_{Q\min} - t(R)_{Q\max}}{t(R)_{Q\min} + t(R)_{Q\max}} \qquad (3)$$

Where $t(R)_{Qmin}$ is the unmasked thickness distribution for Q_{min}, and $t(R)_{Qmax}$the unmasked distribution for Q_{max}. The range of Δ values across all rack radii represents the Uniformity Limit which can be achieved, after masking, for a given Chamber Geometry and range of Source Behaviour.

It is obviously desirable to minimize Δ (R) and thus desensitize the set up. The thickness distributions $t(R)_{Qmin}$ and $t(R)_{Qmax}$ depend on the source offset (S) and so one might expect that adjusting the offset may yield some reduction in Δ .

DELTA PLOTS

We have found that our real sources can have Q values anywhere from O to 4 or more, but many of the dielectric materials which we use most commonly have Qs in the range 1 – 2. Table 1 shows the thickness distributions for these two Q values when the source is in the center, and the corresponding Δ values across the rack.

Table I: Thicknesses & Δs for Central Source
$Q_{min}=1$, $Q_{max}=2$

Rack Radius	t_{Qmin}	t_{Qmax}	Δ
0	100	100	0.0
10	98.0	97.5	0.3
20	92.5	90.7	1.0
30	84.2	80.6	2.2
40	74.3	69.0	3.7
50	64.0	57.2	5.6
60	54.1	46.4	7.7
70	45.0	36.9	9.9
80	37.2	29.0	12.4
90	30.5	22.7	14.7
100	25.0	17.7	17.1

This is simply a tabular representation of the plot in Figure 4. Table 2 shows the corresponding thicknesses and Δ values when the source is moved to an offset of 30%. As we would expect the thickness distributions improved, but in addition, all Δ values are reduced, indicating that by offsetting the source we have decreased the effects of source variation.

Table II: Thicknesses & Δs for Source Offset of 30%
$Q_{min}=1$, $Q_{max}=2$

Rack Radius	t_{Qmin}	t_{Qmax}	Δ
0	100	100	0.0
10	98.6	98.4	0.1
20	94.6	93.7	0.5
30	88.4	86.3	1.2
40	80.4	77.1	2.1
50	71.5	66.8	3.4
60	62.2	56.3	5.0
70	53.1	46.4	6.7
80	44.8	37.5	8.9
90	37.3	29.9	11.0
100	30.9	23.7	13.2

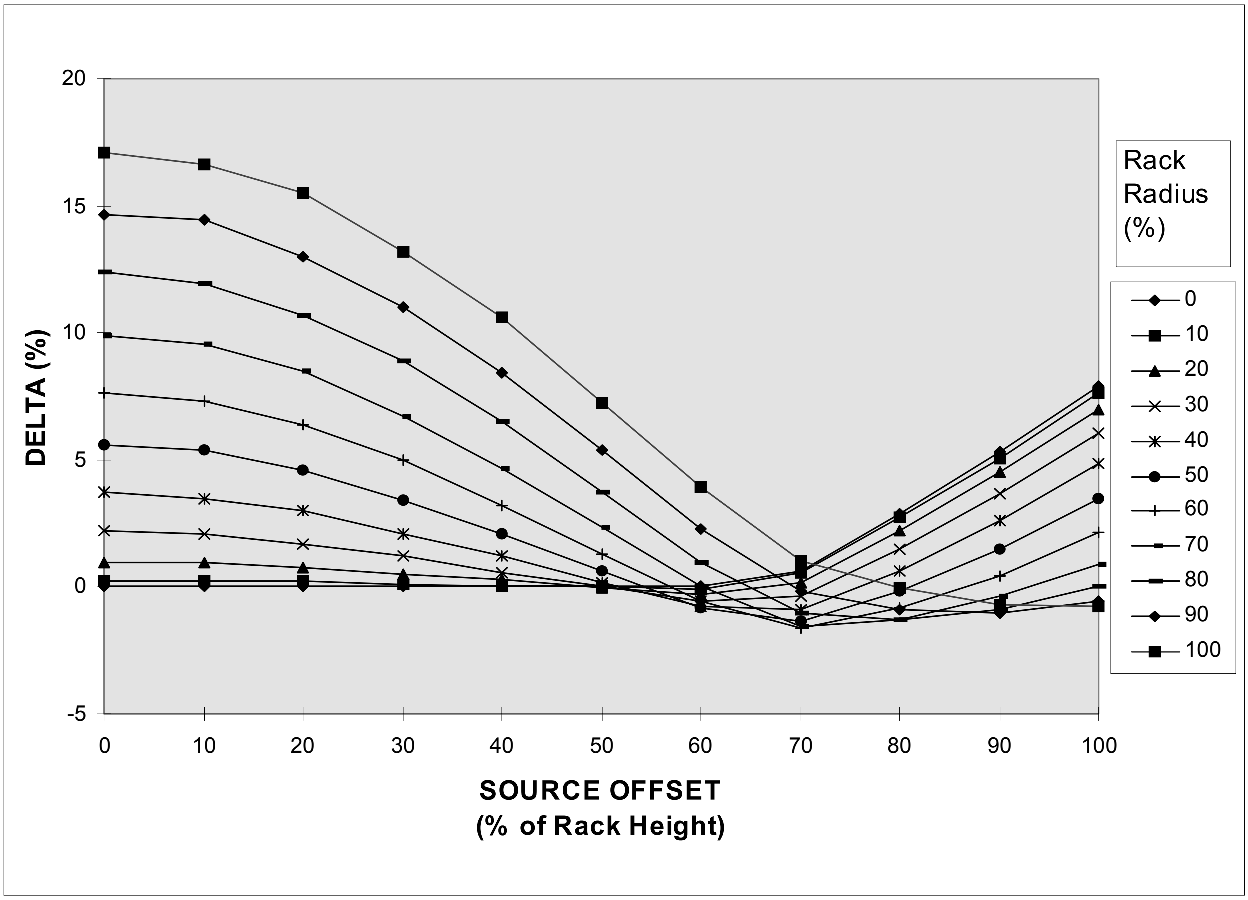

Figure 5: DELTA Plot for Q Range 1-2 (Each line corresponds to a rack radius from 0-100%)

A similar table was generated for every source offset between O and 100%, in increments of 10%. The Δ values for each rack radius could then be plotted against source offset, and the resulting DELTA Plot is shown in Figure 5. Each line in the figure corresponds to a fixed rack radius and reveals how, at that radius, Δ changes as the source is moved from the center to maximum offset. The striking aspect of this figure is the strong convergence of all Δ plots to a minimum at an offset of about 70%. With zero offset, as was seen in Figure 4, Δ near the rack center is near zero, but at the rack edge Δ is large. As the source offset is increased, Δ at the rack edge drops rapidly, but Δ values near the rack center remain small until the offset exceeds 80%.

The predicted non-uniformity for any source offset is given by the spread of Δ values across the rack for that offset. It is clear that for the range of source behavior depicted in Figure 5, the *Uniformity Limit* is about 3% and will be realized when the source is at 70% - the *Optimum Offset.*

It should be pointed out that a source whose Q ranges from 1–2 is not well controlled. However, for a process which involves more than one material we could realistically expect source variations of this magnitude or more. Somewhat less realistic is allowing the rack radius to extend to 100% of the rack height; it is unusual for racks to go beyond 70% of height. Examining Figure 5 again with this in mind, we might eliminate the 3 lines corresponding to the outer 30% of the rack. Now an even tighter convergence can be achieved with an Optimum Offset of 60%, and the Uniformity Limit is reduced to about 1%.

So far we have only examined one range of source behavior. We generated thickness distributions for all ***Q*** values from 0 to 4 in increments of 0.5 and constructed Δ plots for all permutations. In every case the pattern is the same: there is always a minimum, but, as one would intuitively expect, the quality and location of the minimum depend on the range of ***Q*** used for the plot. Two examples serve to illustrate:
In Figure 6 the source ***Q*** varies over a wider range, from 0.5 to 2.5. There is still a clear minimum, but the uniformity limit in this case has increased to ~5%, and on either side of the minimum the plots rise, steeply indicating that the arrangement will be sensitive to the precise location of the source.

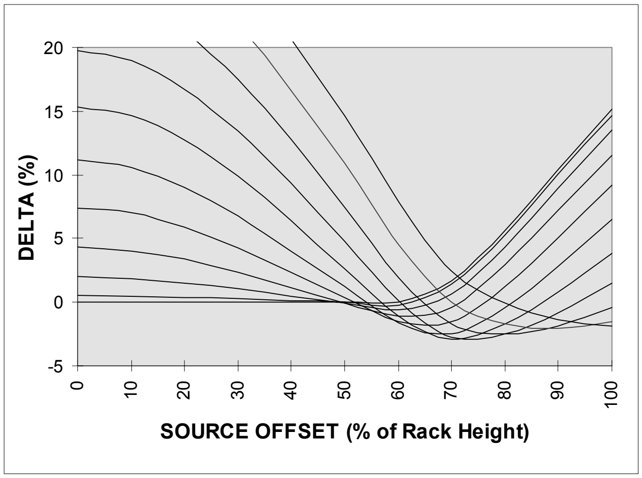

Figure 6: DELTA Plot for Q Range 0.5 - 2.5

Figure 7 shows a much better controlled source, Q ranging from 1.5 to 2.0 and in this case the plots are tightly grouped, converging gently to a minimum for a Uniformity Limit of ~1%.

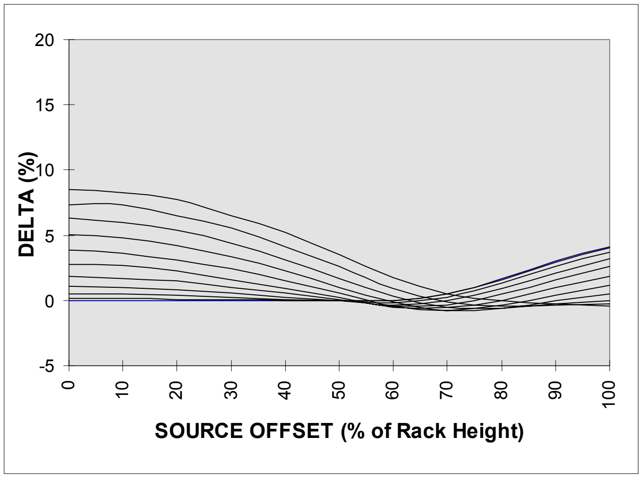

Figure 7: DELTA Plot for Q Range 1.5 - 2.5

Through these plots it is clear that no matter how small or large the range of source emission characteristics, there is always a source offset which minimizes the thickness non-uniformity caused by that range of source behaviors.

SOURCE RELATIONSHIPS

It is apparent that, in dealing with real sources, we cannot think in terms of a single Q value, but must assign a range such as $Q_{min} - Q_{max}$. In looking for trends it is convenient to characterize the source by two values:

The Average Q:

$$Q_{ave} = \frac{Q_{\min} + Q_{\max}}{2}$$

and the range of Q:

$$dQ = Q_{\max} - Q_{\min}$$

In setting up a process in a chamber, there are two key considerations related to source behavior: *Optimum Offset* and *Uniformity Limit*. We might ask how they are influenced by Q_{ave} and dQ. In Figure 8, Optimum Offset is plotted against Q_{ave} All values of dQ are included in these plots and it can be seen that the best offset is inversely proportioned to Q_{ave} and completely independent of dQ. Two sets of data are shown, one for a maximum rack radius of 70% and one for 100%. In both cases the relationship is the same, but the larger rack diameter requires greater source offsets. Although it is not apparent from this figure, the larger rack diameter also resulted in higher Uniformity Limits.

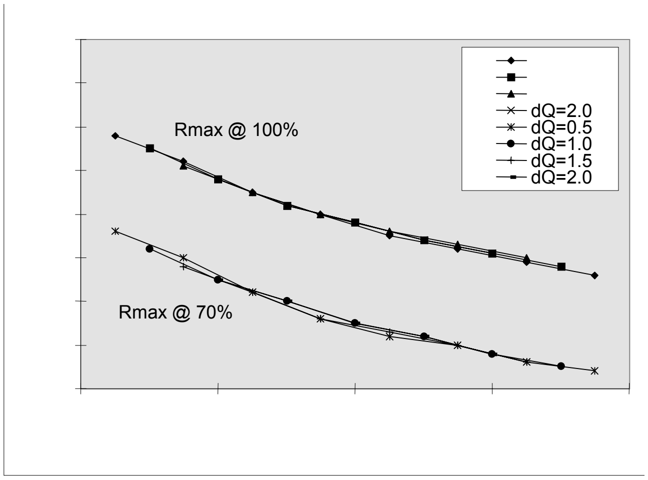

Figure 8: Optimum Offset vs Qave

In Figure 9 we see how the Uniformity Limit depends on dQ . Again, two sets of data are shown for 70% and 100% rack radii. For each value of dQ, all values of Q_{ave} are plotted. While the Uniformity Limit is largely governed by the value of dQ, there is some dependence on Q_{ave} which results in a spreading of the plotted points, the larger Limits coming from the higher Q_{ave} values.

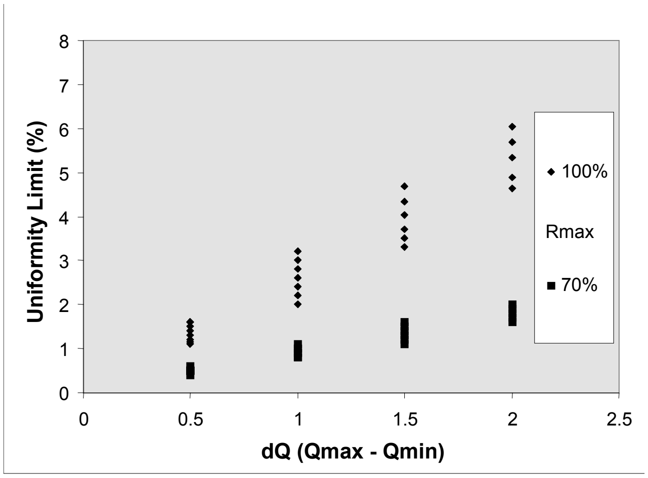

Figure 9: Uniformity Limit vs. ***dQ*** - 2 data sets are shown, for maximum rack radii of 70% and 100%

We can now return to the case which was first considered, that of a source varying from ***Q***=1 to ***Q***=2 (ie. Q_{ave}=1.5 and ***dQ***=1). When such a source is centrally located, the Uniformity Limit is shown in Figure 4. From Figures 8 and 9 we can determine that the Optimum Offset for such a source should be ~70% (assuming a maximum Rack Radius of 100%) and that the Uniformity Limit will then be 3%.

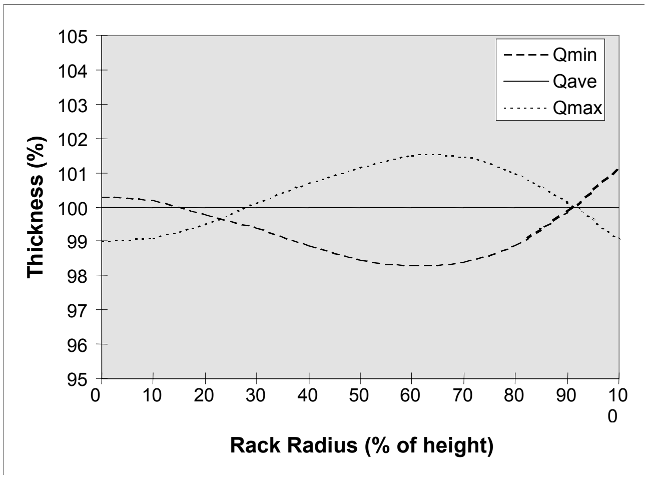

Figure 10: Uniformity Limit at Optimum Offset (Source ***Q*** Ranges from 1 - 2)

This is illustrated in Figure 10, which shows the predicted thickness distributions, after masking, for the range of source behaviour. When Figure 10 is compared to Figure 4, we can see a vast improvement. Simply by moving the source to its optimal position we have reduced the non-uniformity by a factor of 6. However, if 3% thickness errors are still too large, it is now clear what must be done to improve the situation. For example, Figure 9 shows that to achieve 0.5% uniformity we must restrict the rack radius to 70% of height and limit the source variations to 0.5. Then the Optimum Offset, from Figure 8, would be about 58% for Q_{ave} of ~2.

LIMITATIONS OF THE MODEL

Several assumptions have been made in developing this model:

- That $\cos^{Q}$ is a good description of the source
- That there are no azimuthal variations in the source emission pattern
- That evaporation rate is constant
- That changes in source emission are gradual

Our feeling is that the most serious of these is azimuthal variation, which we already know to be significant for some sources. How this might affect the practical implementation of the model remains to be seen.

CONCLUSIONS

It has been shown that Source Behaviour, Source Offset, Rack Diameter and Thickness Uniformity are all related and must be considered together when designing a chamber layout. The exact approach will depend on the circumstances: if maximizing rack capacity is important and there is some flexibility in choice of coating materials, evaporants might be selected on the basis of their similar ***Q*** values and the process designed to tolerate the non-uniformity inherent in a large rack.

On the other hand, if performance requirements dictate a high degree of thickness control and material choices are limited, it may be necessary to reduce the rack size to achieve the necessary uniformity

Whatever the situation, this work proposes a method for determining the best source location, based on knowledge of that source's behaviour. The effectiveness of this method as a practical tool in process design will be reported at another time.

REFERENCES

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3. H. A. Macleod, Thin-Film Optical Filters, 2nd Edition, Macmillan, p.420