Neutron Guides

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1 Introduction

A Working Group was set up to investigate the implications of using guides on the Rutherford Laboratory SNS in July 1978; its first report was published in November 1979(1). The main differences between steady state and pulsed source neutron instruments are that the latter necessarily view smaller moderator areas, and also that their lengths are primarily determined by time-of-flight resolution requirements. Both these factors affect the design of guides. Our study to date has concentrated on optimising the design of guides for two typical pulsed source instruments viz

(a) a 100 m long high resolution backscattering powder diffractometer (HRPD) which uses both thermal and cold neutrons, and

(b) a 40 m long high resolution backscattering inelastic spectrometer ('IRIS) which uses cold neutrons.

The properties of the various guide arrangements possible for these instruments were predicted using a new Monte Carlo code(2). This paper summarises some of the most important conclusions of the Working Group up to the present.

2 Computer Simulation - MCGUIDE

It is only in the case of continuous straight guides that analytical expressions give an adequate description of real (ie imperfect) three-dimensional guides. All SNS guides are circularly curved and of length greater than the direct line-of-sight and the Monte Carlo code MCGUIDE(2) was written to simulate their behaviour. The code is very versatile and includes the following features:

a) the simulation of combinations of straight, curved, and tapered guide sections,

b) the provision of spaces between guide sections for other instrument components, and

c) allowance to be made for reflectivity losses due to surface waviness.

It has proved particularly valuable in predicting the spatial asymmetry in beams from curved guides and the effects of guide losses. The code has been extensively tested and it has been used to obtain most of the results presented in this paper.

3 Guide and Sample Illumination

The moderator areas at reactor sources (eg ILL) are generally large in comparison with guide dimensions and relatively little attention has been paid in the past to matching the source and guide areas so as to ensure complete illumination. Source-guide entrance matching is however very important for longer wavelength neutrons where the guide's solid angle of acceptance is large, and for cold sources which have relatively small source areas it is apparent that complete illumination is not always achieved at reactor installations. At accelerator based neutron sources, where the moderator areas are even smaller, incomplete illumination can occur even in the thermal neutron range unless the guide entrance is placed sufficiently close to the source.

The problem can be treated geometrically in one plane with the aid of the ray diagram shown in Figure 1a. The moderator (dimension m) illuminates a straight guide (dimension g) which transports the neutrons to the scattering sample (dimension s). The moderator to guide entrance distance is L_i, and the exit to sample distance is L_e. In most cases of practical importance for pulsed sources the condition $m > g > s$ applies.

We shall be concerned with nickel guides in which we assume that total reflection occurs at all glancing angles γ less than the critical glancing angle $\gamma_c = 0.0017\lambda$ rad; λ is the neutron wavelength in Å. Complete guide illumination occurs if the λ-dependent maximum guide solid angle $4\gamma_c^2$, when projected from any point on the guide entrance to the plane or the source, is completely covered by the source area. Complete sample illumination occurs if the maximum guide solid angle $4\gamma_c^2$, when projected from any point on the sample to the guide exit plane, is completely covered by the guide exit aperture.

Illumination matching of the guide at a particular wavelength λ occurs when the rays joining the extreme edges of the moderator and the guide entrance are inclined to the guide axis at the critical glancing angle γ_c for that wavelength. Illumination matching of the sample follows the same behaviour (see Figure 1a). For nickel guides the matching conditions are expressed as follows:

$$0.0017\lambda_M = \frac{(m-g)}{2L_i} \text{ , and} \tag{1}$$

$$0.0017\lambda_M = \frac{(g-s)}{2L_e} \text{ .} \tag{2}$$

These equations may be combined to give the complete matching condition for nickel guides:

$$\lambda_M = 294 \frac{(m-s)}{(L_i+L_e)} \tag{3}$$

This matched condition is conveniently represented by the ray diagram shown in Figure 1b. In any practical situation m is fixed by the source (eg m $\sim$ 10 cm for a moderator on the Rutherford Laboratory spallation neutron source), s is fixed by instrument resolution requirements and λ_M is selected to correspond to the critical glancing angle at the longest wavelength at which complete illumination is required. A selection of these three parameters fixes (L_i+L_e), the combined moderator-guide entrance and guide exit-sample distances. The value of the guide dimension g can be selected according to the limiting rays in Figure 1b for either fixed L_i or fixed L_e.

Table 1 shows calculated values for L_i and L_e for different values of the guide dimension g and at different wavelengths, but at constant (m-s) = 7 cm.

λ_M (Å)	(L_e+L_i) (m)	*g = 4 cm*		*g = 5 cm*		*g = 6 cm*	
		L_i(m)	L_e(m)	L_i(m)	L_e(m)	L_i(m)	L_e(m)
1	20.6	17.65	2.94	14.70	5.89	11.77	8.82
2	10.3	8.83	1.47	7.35	2.94	5.88	4.41
3	6.86	5.88	0.98	4.90	1.96	3.92	2.94
4	5.15	4.41	0.74	3.68	1.47	2.94	2.21
5	4.12	3.53	0.59	2.94	1.18	2.36	1.76
6	3.43	2.94	0.49	2.45	0.98	1.96	1.47
8	2.58	2.21	0.37	1.84	0.74	1.48	1.10
10	2.06	1.77	0.29	1.47	0.59	1.18	0.88

Table 1 Calculated L_i and L_e values at the matched condition for different guide dimensions and wavelengths but fixed moderator and sample dimensions.

For $\lambda<\lambda_M$ the gain factor G in the neutron flux transported by a straight guide over that observed at the end of a non-reflecting collimator is simply the ratio of the 'conducting' solid angle of the guide to the solid angle subtended by the source at the exit of the guide. This is given (for nickel guides) by:

$$G = 1.15 \times 10^{-5} \left[\frac{\lambda L}{m}\right]^2 , \tag{4}$$

ie the gain at wavelengths $<\lambda_M$ is proportional to λ^2.

For $\lambda>\lambda_M$ the gain factor *G continues to increase up to a saturation wavelength* λ_s which is the longest wavelength that can be reflected by the guide at the extreme reflection angles connecting the bottom (or top) of the moderator to the top (or bottom) of the guide. λ_s defines the wavelength at which no further gains ensue. This effect is demonstrated in curve B of Figure 2 where the results were obtained using the Monte Carlo simulation code MCGUIDE.

4 Beam Asymmetry in Curved Guides

One of the problems associated with curved guides is the non-uniform radial intensity distribution at their exits. This non-uniformity is wavelength dependent, and is particularly pronounced at wavelengths less than the characteristic wavelength λ^{*}[†] where the only mode of neutron transport is by garland reflections on the outer wall of the guide.

For a perfect rectangular cross-section curved guide which is uniformly illuminated, the radial distribution at a distance greater than the 'line-of-sight' may be derived analytically:

$$T = \cos^{-1}\left\{\frac{1-\gamma_c^2/2}{1-(f\gamma^{*2})/2}\right\}\Big/\gamma_c = \left[1 - f\left(\frac{\gamma^*}{\gamma_c}\right)^2\right]^{\frac{1}{2}}, \qquad (5)$$

where T = transmission relative to that of a single straight guide, and

f = fractional distance across the guide exit aperture measured from the outer wall.

The variation of T with f at various values of λ/λ^* ($= \gamma/\gamma^*$) is shown in Figure 3.

It is possible to reduce this asymmetry by adding a straight guide section as the last component in a curved guide system. However, there are no analytic descriptions of curved-straight systems, and to investigate the length of the straight section required for a uniform distribution the computer code MCGUIDE was employed to study a number of curved/straight guide systems. This exercise revealed an interesting effect in curved/straight guide combinations which, while qualitatively predictable from simple guide theory, would be difficult to quantify. This effect may be described as a transverse wave which arises in the following way:

For neutrons with wavelengths $\lambda < \lambda^*$, the radial distribution at the end of the curved section is asymmetric and bunched at the outer guide wall. The resulting angular/space correlation gives a dispersing transverse wave which travels down the guide. Neutrons thus appear to 'wash' from one side of the guide to the other. The important fact to emerge is that, for a particular wavelength, there are points along the straight sections of the guide at which the transverse distribution is more uniform than at other points further down the guide. Furthermore, although increasing the straight section at the end of a curved guide generally results in an improvement in beam uniformity, there are also positions along the straight section which give rise to a high non-uniformity at particular wavelengths. These points are illustrated in Figure 4 where the transverse distribution of neutrons with λ = 1.0 Å in a 8 cm x 2.5 cm guide have been plotted at 70 m, 80 m, 90 m and 100 m along curved/straight guide systems. In this example the guide is curved (with R = 18 km) from 1 m to 60 m, the line-of-sight distance.

However, in deciding the 'best' straight section length for a particular instrument it is the uniformity at the sample position which is important. This can be quite different from that at the guide exit since, for example, neutrons could be uniformly distributed across the guide exit while having a non-uniform angular distribution. This effect has been studied for the HRPD instrument (Figure 5) for different aperture widths w and straight section lengths using MCGUIDE. Three guide widths were chosen (w = 2.0, 2.5 and 3.0 cm) and for each width a radius was chosen so that line-of-sight occured at the end of a 60 cm curved section. The guide parameters were as follows:

w(cm)	R(km)	λ^*(Å)	L_o(m)
2.0	22.5	0.78	60
2.5	18.0	0.98	60
3.0	15.0	1.18	60

A series of 10 m straight sections were then added, and the intensities on two halves of a 2 cm wide sample (at 2 m from the guide exit) were simulated for total guide lengths of 70, 80, 90 and 100 m. The results for a guide width w = 2.5 cm are shown in Figure 6 for λ = 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6 Å. This illustrates that 'nodes' occur in the intensity distributions and that as λ decreases, the straight section must be longer for equalisation of the beam. From these results it would appear that a

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[†] The properties of a circularly curved guide are determined by a characteristic angle γ^* - the angle between a line-of-sight and the tangents at the start or finish of the line-of-sight. To good approximation $\gamma^* = (2a/R)^{\frac{1}{2}}$ where 'a' is the guide width in the plane of curvature and R is the radius of curvature. λ^* is the critical wavelength at the characteristic angle ie $\lambda^* = \gamma^*/0.0017$ for nickel.

final straight section of length 35 - 40 m would prove adequate at all the wavelengths for the HRPD guide.

5 Guide Losses

principal loss mechanisms that we have considered are those due to abutment errors and surface waviness. Analytic calculations for both these losses have been performed; the MCGUIDE simulations were consistent with these calculations.

A detailed treatment of abutment errors has been reported(3). Figure 7 shows the magnitude of the transmission losses calculated for the HRPD guide as a function of wavelength at three values of the abutment error σ. These losses are tolerable for $\sigma < 0.0025$ cm - a value which is technically feasible.

The other loss which has been thoroughly investigated is that due to surface waviness(4), particularly in the context of relaxing the surface quality of the guide sections nearest the source. Following reports of radiation damage in the ILL neutron guides(5), it was decided to study the effect of using more radiation-resistant mirror materials with a more inferior surface quality than glass (eg polished metals) as the early guide sections.

Any losses incurred this way are more crucial for the 'IRIS guide (Figure 8) which uses long wavelength neutrons and needs to start at approximately 2 m from the source to ensure complete illumination. Figure 9 shows the % loss in intensity computed as a function of wavelength for different values of surface waviness in guide section 1 (in-shutter) of 'IRIS (see Figure 8), where a 0.0005 rad waviness is assumed to give zero loss(6). Surface waviness is treated in MCGUIDE by randomising the local shape at each reflection point about an angle $\pm \beta$ in two dimensions. Further calculations showed that a relaxation of the surface waviness of all the "in-shield" sections of the 'IRIS guide from 10^{-4} to 10^{-3} radians causes intensity losses < 5%. It was concluded that inferior surface quality guide sections could certainly be used in the shutter without significant losses in flux.

6 Guide Bunching

A study has been made of the implications of multiplexing neutron guides on the SNS(7). The obvious advantage of multiplexing beam holes or guides in what is normally a single neutron beam sector around the source is one of neutron economy. The main disadvantages are i) a weakening of the shielding, ii) instrument crowding and iii) the need for additional beam shutters per sector, so that the instruments can be used independently.

A major constraint on the design of pulsed source neutron scattering instruments arises from the need to utilise disc choppers both to prevent frame overlap and to define the incident energy window. Since the efficiency of a disc chopper increases with its diameter it is desirable that these are made as large as possible. The disc chopper design consequently leads to a minimum separation of adjacent neutron beams. The use of disc choppers close to the source (5 - 12 m) is particularly important for instruments situated on long guides (25 - 100 m). It was originally believed that a guide bunch of three could be incorporated into a SNS instrument sector (nominally ∿ 13°) without undue congestion(1). Further detailed design work has shown that this is not advisable. The present policy being adopted on the SNS is that the multiplexing of guides should be limited to guide pairs.

7 Current Development Work

Several 1 metre long prototype guide sections are now being commercially produced in the UK. These are due to be delivered at the Rutherford Laboratory early in 1981 and will be tested optically(8). A survey is being made of the commercially available glasses that can be used in neutron guides. The final choice of the glass will depend on the results of neutron irradiation tests carried out under conditions designed to simulate ∿ 5 years of SNS use.

References

[1] "Neutron Guides on Pulsed Sources" - C J Carlile, M W Johnson and W G Williams, Rutherford Laboratory Report RL-79-084.

[2] "MCGUIDE: A Thermal Neutron Guide Simulation Program" - M W Johnson, Rutherford Laboratory Report RL-80-065.

[3] M W Johnson - Rutherford Laboratory Guides Working Party, GWP/4/80, "Losses in neutron guies due to abutment errors".

[4] M W Johnson - Rutherford Laboratory Guides Working Party, GWP/3/80, "Transmission losses in initial neutron guide sections: some analytic results".

[5] P Ageron, P Blum - ILL, private communication.

[6] J Penfold - Rutherford Laboratory Guides Working Party, GWP/5/80, "Futher calculations of the neutron flux dependence on the surface quality of the "in-shield" sections of the 'IRIS guide".

[7] W G Williams, C J Carlile - Rutherford Laboratory Guides Working Party, GWP/1/80, "Beam hole multiplexing and possible uses for restricted access neutron beams on the SNS".

[8] C J Carlile, J Penfold - Rutherford Laboratory Guides Working Party, GWP/6/80, "Proposal for testing neutron guides".

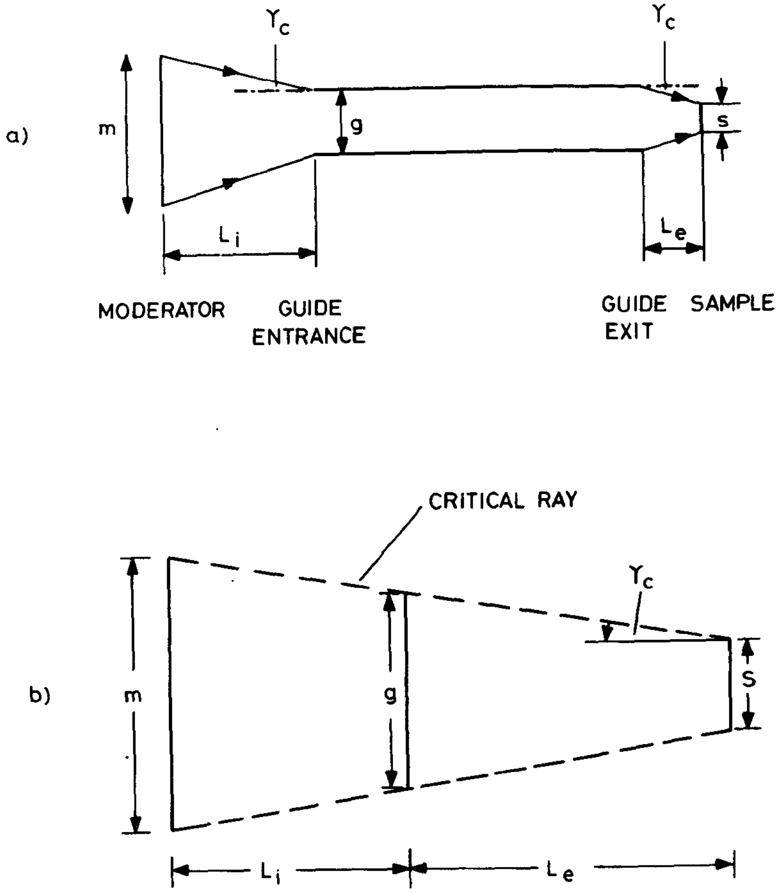

FIGURE 1. ILLUMINATION MATCHING OF GUIDE WITH MODERATOR AND SAMPLE

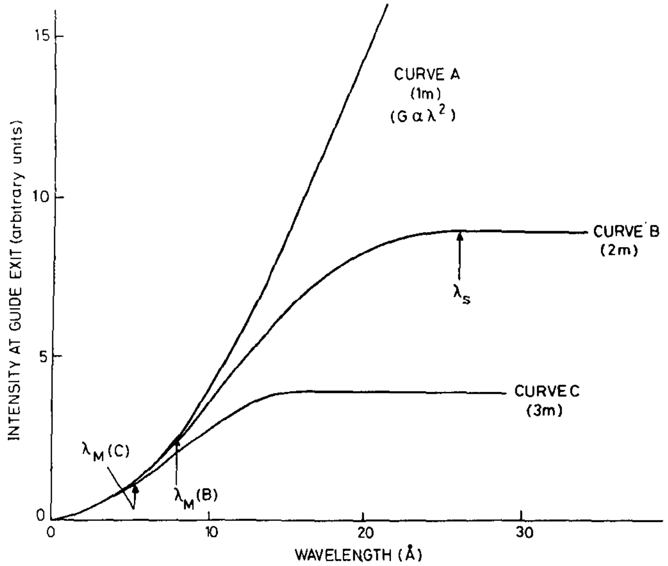

FIGURE 2. INTENSITIES AT EXIT OF STRAIGHT GUIDE AT 12m FROM SOURCE FOR DIFFERENT MODERATOR – GUIDE ENTRANCE DISTANCES

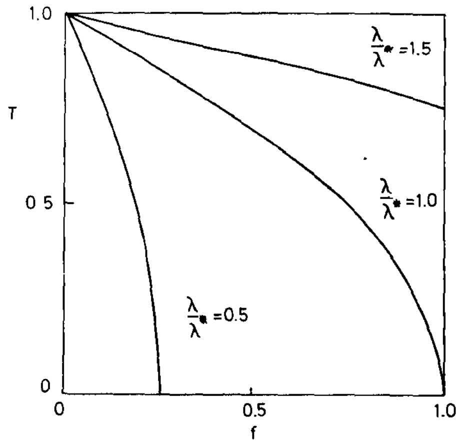

FIGURE 3. CURVED GUIDE TRANSMITTANCES (T) AS A FUNCTION OF FRACTIONAL DISTANCE ACROSS THE GUIDE APERTURE (f) FOR DIFFERENT λ/λ^*

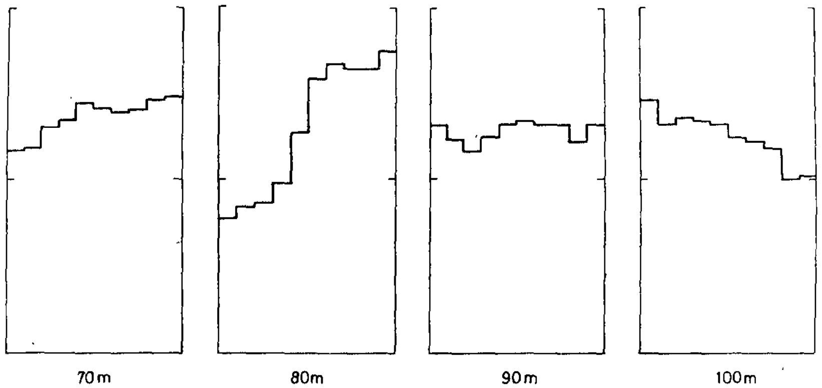

FIGURE 4. TRANSVERSE NEUTRON DISTRIBUTIONS AT λ = 1Å IN A (2.5cm x 8cm) CURVED – STRAIGHT GUIDE WITH A CURVED SECTION LENGTH L_c = 60m AT DIFFERENT POINTS ALONG THE STRAIGHT SECTION

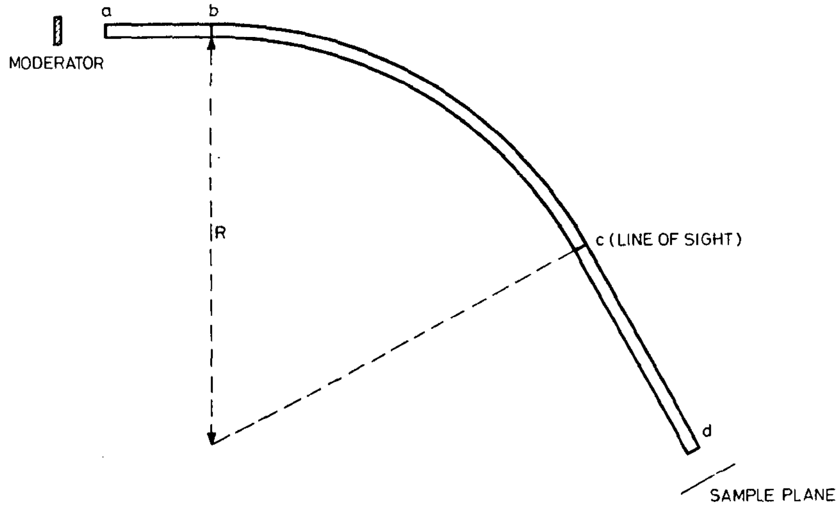

FIGURE 5. ELEMENTS IN GUIDE SYSTEM FOR HRPD INSTRUMENT

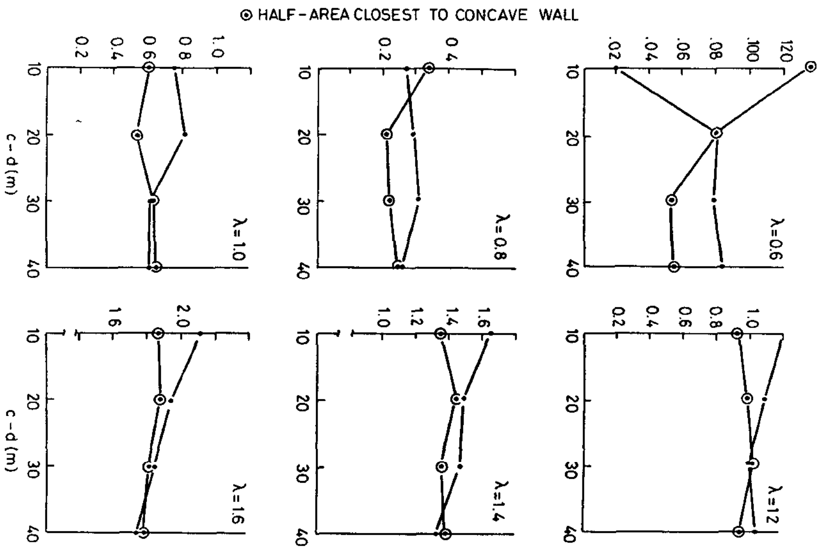

FIGURE 6. INTEGRATED INTENSITIES ON TWO HALVES OF SAMPLE AREA FOR 10m, 20m, 30m AND 40m STRAIGHT SECTIONS ON THE HRPD GUIDE; 0.6<λ(Å)<1.6

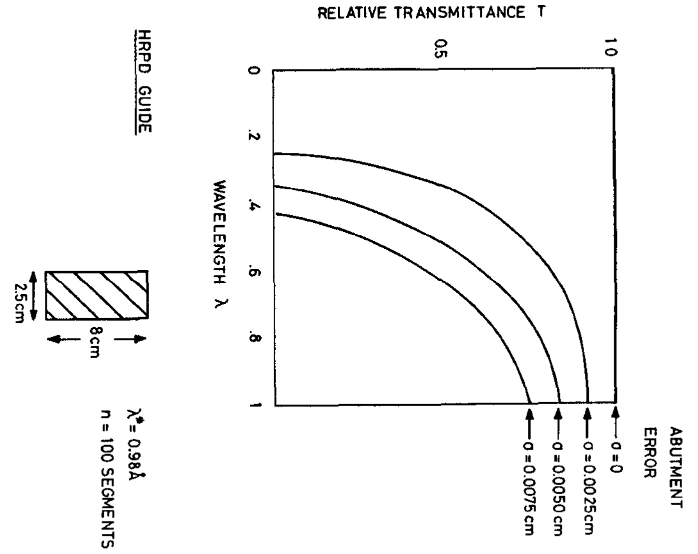

FIGURE 7. EFFECT OF ABUTMENT ERROR ON TRANSMITTANCE OF HRPD GUIDE.

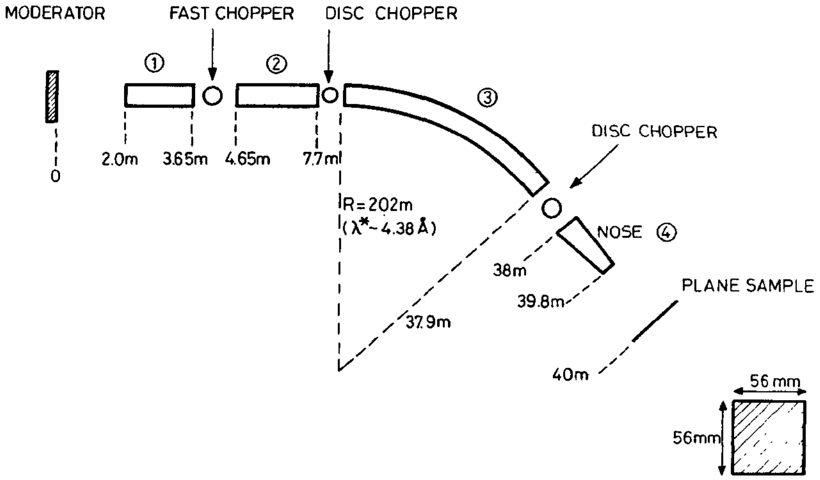

FIGURE 8. SCHEMATIC OF GUIDE SYSTEM FOR THE HIGH RESOLUTION QUASIELASTIC SPECTROMETER 'IRIS

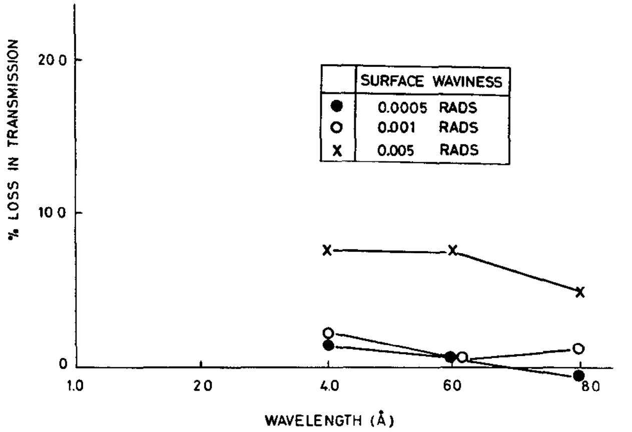

FIGURE 9. % LOSS OF INTENSITY IN IRIS GUIDE THROUGH VARYING THE SURFACE QUALITY IN THE FIRST 1.65m SECTION