Neutron Guides on Pulsed Sources

C J Carlile, M W Johnson and W G Williams

November 1979
CONTENTS

1 INTRODUCTION

2 NEUTRON CONDUCTION IN GUIDES
   (a) Basic Theory
   (b) Loss Mechanisms in Guides
      i) Penetration depth
      ii) Microscopic surface defects
      iii) Macroscopic surface defects
      iv) Reflectivity losses due to imperfect mechanical construction
   (c) Guide Illumination
   (d) Computer Simulation

3 APPLICATION TO PULSED SOURCES
   (a) General Considerations
      i) Matching of source and guide solid angles
      ii) Converging guides
      iii) Path length uncertainties
      iv) Beam divergence and Q-resolution
      v) Beam asymmetry
      vi) Guide bunching
   (b) The High Resolution Powder Diffractometer Guide
   (c) The High Resolution Quasielastic Spectrometer Guide

4 PRACTICAL ASPECTS OF GUIDE CONSTRUCTION
   (a) Garching Guide for TOF Powder Diffractometer
   (b) Radiation Damage in Neutron Guides

5 OUTSTANDING PROBLEMS

ACKNOWLEDGEMENTS

REFERENCES

NEUTRON GUIDES ON PULSED SOURCES

C J Carlile, M W Johnson and W G Williams

A survey of the physics of neutron guides has been applied to their installation on pulsed neutron sources, particularly the Spallation Neutron Source (SNS) at the Rutherford Laboratory. Guides on pulsed sources generally view smaller source areas than those on continuous sources, and furthermore their lengths are fixed primarily by time-of-flight resolution requirements. These differences have been accounted for in the design of guides for two SNS instruments. A Monte Carlo computer code has been used in the optimisation and simulation of the guide geometries.
INTRODUCTION

The effectiveness of neutron guides in transporting thermal and cold neutrons over distances ~ 100 m is now universally recognised following the extensive use of guides at the high flux reactor at the Institut Laue-Langevin, Grenoble (1). The main advantages of guides are a) they give large intensity gains over non-reflecting collimators since they can transport neutrons without loss in solid angle, b) curved guides can be used to 'filter out' fast neutrons and γ's, and c) the neutrons can be transported to spacious experimental regions where there are low backgrounds. The main purpose of the present study was to investigate the implications of using guides at the Rutherford Laboratory Spallation Neutron Source. A Working Group was set up for this purpose in July 1978, and this report summarises the work of that group up to November 1979.

The main differences between steady state and pulsed source neutron instruments are that the latter generally 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

1. a 100 m long high resolution backscattering powder diffractometer (HRPD) which uses both thermal and cold neutrons, and
2. a 40 m long high resolution backscattering inelastic spectrometer ('IRIS') which uses cold neutrons.

In considering the design of these instruments we have reviewed the now well-established physics for describing the beam transport, and predicted the properties of various guide arrangements using a Monte Carlo code especially written for this purpose. The code allows for i) reflectivity losses in the guides and ii) the provision of spaces in the guides for other instrument components. It has proved invaluable in predicting the spatial asymmetry in beams obtained from curved guides.

Some thought has also been given to the practical aspects of guide design, particularly the implications of guide bunching, guide tapering, and guide alignment. Finally, some outstanding problems have been identified for future investigations.

NEUTRON CONDUCTION IN GUIDES

(a) Basic Theory

The phenomenon of total reflection for neutrons was first demonstrated in 1946 (2,3) and applied to the development of neutron guides or conducting tubes in the early 1960's (4). The maximum angle at which this occurs we denote as the critical glancing angle γc, and this is related to the refractive index n of the mirror material for 'in vacuo' reflections by

\[ \cos \gamma_c = \frac{n}{\gamma} \]  \hfill (2.1)

For thermal and cold neutrons we shall be concerned with glancing angles of incidence where \( \sin \gamma \approx \gamma \), and

\[ \gamma_c^2 = 1 - \frac{n^2}{\gamma^2} \]  \hfill (2.2)

For perfect mirror surfaces the reflectivity \( R \) is unity at incident glancing angles \( \gamma < \gamma_c \), and falls off at angles \( \gamma > \gamma_c \) according to the relationship (5)

\[ R = \frac{\left(\frac{n^2 - \cos^2 \gamma}{\gamma^2}\right) \frac{\sin \gamma}{\left(\frac{n^2 - \cos^2 \gamma}{\gamma^2}\right) + \sin \gamma}^2}{2} \]  \hfill (2.3)

which for small angles may be written as
The dependence of the reflectivity coefficient on the reflection angle is shown in Figure 1.

The 'in vacuo' refractive index \( n \) is related to the neutron wavelength \( \gamma \) and the average bound coherent scattering amplitude \( B \) of the reflecting medium by

\[
\frac{n^2}{\gamma} = 1 - \frac{B}{N N_{a}} \tag{2.5}
\]

where \( N \) is the mean atomic number density. We can therefore express the critical glancing angle for the so-called mirror reflection in terms of the coherent scattering density \( (N N_{a}) \) of the mirror material:

\[
\gamma_{c} = \frac{1}{N N_{a}} \tag{2.6}
\]

and since \( B \) is positive for most mirror materials, \( \gamma_{c} \) turns out to be real. In order to achieve the largest possible range of reflection angles at a given wavelength it is important to use mirror materials which have the highest coherent scattering densities. In this report we shall be solely concerned with reflection from nickel surfaces where \( (\gamma_{c}/\lambda) \approx 0.0017 \text{ rad} \text{Å}^{-1} \), this being the largest value of readily available mirror materials.

The principal advantage of neutron guides is that they enable neutrons to be transported over large distances within solid angles \( \approx 4\gamma_{c}^2 \) with little loss of intensity and over areas determined by the guide's cross-section. 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, assuming complete illumination of the guide entrance, 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. For nickel guides used to conduct neutrons of wavelength \( \lambda \) (Å) over a distance \( L \) (m) from a square source of sides \( m \) (cm) this gain is

\[
G = 1.15 \times 10^{-5} \left( \frac{L}{m} \right)^2 \tag{2.7}
\]

and typical values are shown in Figure 2. The requirements for complete guide illumination are discussed in Section 2c.

The maximum number of reflections possible in a straight guide of length \( L \) and rectangular cross-section \((a \times b)\) is given by

\[
n_{\text{max}} = \gamma_{c} \left( \frac{1}{a} + \frac{1}{b} \right) L \tag{2.8}
\]

and, assuming an isotropic distribution of neutrons within \( \gamma_{c} \), the average number of reflections is

\[
n_{\text{av}} = \frac{\gamma_{c}}{2} \left( \frac{1}{a} + \frac{1}{b} \right) L \tag{2.9}
\]

The number of reflections in a rectangular guide is frequently, and often more conveniently, expressed in momentum space \((n k = 2\pi k_{a}/\lambda))\). For a coordinate system where the \( x \) and \( y \) directions are defined along the \( a \) and \( b \) guide dimensions, and \( z \) corresponds to the guide axis

\[
n(k) = \frac{L}{a} k_{x} + \frac{L}{b} k_{y} \tag{2.10}
\]

where \( n_{a} \) and \( n_{b} \) represent the components of the neutron momentum along the respective axis \((\lambda)\).

Although straight guides are useful in conducting neutrons over large distances their exits directly view the neutron source, and particularly for accelerator based sources this could mean that large fast neutron and \( \gamma \) fluxes might reach the scattering samples. These fluxes can be appreciably attenuated by circularly curving a guide over a length greater than the "direct line of sight" \( L_{o} \). For a guide which
is curved in the horizontal plane, and which has an aperture dimension "a" in this plane:

\[ L_0 = \sqrt{8aR} \quad (2.11) \]

where \( R \) is its radius of curvature and \( a < R \). The displacement \( \delta \) of the guide axis over the distance \( L_0 \) is

\[ \delta = \frac{L_0^2}{2R} = 4a \quad (2.12) \]

The characteristic angle \( \gamma^* \) of a circularly curved guide is defined as the angle between a line of sight and the guide axis at the start or finish of the line of sight (see Figure 3). To good approximation:

\[ \gamma^* = \sqrt{\frac{2a}{R}} \quad (2.13) \]

Neutrons with wavelengths \( \lambda < \lambda^* \) are transmitted only by single or multiple (garland) reflections on the concave surface of the guide, whereas those with wavelengths \( \lambda > \lambda^* \) are transmitted by zig-zag (from both concave and convex surfaces) as well as single and garland reflections. The guide's transmittance thus decreases towards shorter \( \lambda \), since the smaller \( \gamma^*_c \) values mean that neutrons can only emerge from the guide at smaller solid angles near the concave surface. A further consequence is that the spatial distribution of the neutrons at the guide exit is asymmetric at \( \lambda \approx \lambda^* \), and that this asymmetry rapidly worsens as \( \lambda \) decreases \((7)\).

The number of reflections in a curved guide depends on the spatial and angular coordinates of the entrant neutron as well as its wavelength. Alefeld et al\((6)\) have treated the problem analytically for the two-dimensional case. In this work we have treated the problem by following the trajectory of each neutron individually using a Monte Carlo code (see section 2d). Although the "line of sight" length \( L_0 \) is the minimum length which ensures that each neutron must undergo at least one reflection in the guide, in practice curved guides are usually constructed with lengths greater than \( L_0 \).

Curved guides are in general used in combination with shorter sections of straight guides. There is almost invariably a straight section within the beam plug close to the source. It can also be advantageous to add a straight section at the end of a curved guide since this tends to diminish the spatial asymmetry of the emergent beam, particularly at shorter wavelengths. For a guide combination with a curved section of length \( L_C \) and a straight section \( L_s \) the deflection \( \delta \) of the guide axis is given by

\[ \delta = \frac{L_C}{2R} (L_C + 2L_s) \quad (2.15) \]

where \( R \) is the radius of curvature of the curved section. In order to avoid having an excessively long combined 'line of sight', the length of the curved section \( L_C \) should approach the 'line of sight' length \( L_0 \) of this section. The 'line of sight' length of the combination \( L_1 \) is given by

\[ L_1 = \left[ \frac{\hat{c}^2}{2F - 1} \right] L_0 \quad (2.16) \]

where \( F = L_C/L_0 \). Figure 4 shows a plot of \( (L_1/L_0) \) vs \( F \) and illustrates the importance of making the length of the curved section in curved-straight guides as large as possible compared to the curved line of sight (eg \( L_C/L_0 = F > 0.75 \)) since this shortens \( L_1 \) and the total length of the combination. The assessment of the properties of different straight guide-curved guide combinations is too complex to be treated analytically. The best method is to carry out a Monte Carlo simulation of the neutron transport through the combination and this is described in Section 2d.

(b) Loss Mechanisms in Guides

The theory described in Section 2a applies to ideal guides which are perfectly smooth, continuous, and which have reflectivities of 100%. There are several mechanisms which cause a guide's transmission to be less than that calculated using these naive assumptions and these are now discussed.
i) Penetration depth

As the neutron wave penetrates the reflecting medium its amplitude decreases exponentially with depth, $x$, as follows:

$$ A_x = A_0 \exp\left(-\frac{x}{d}\right) \quad (2.17) $$

where $d$ is the $1/e$ penetration depth for the medium at a particular reflection angle $\gamma$. If $\gamma$ is small, as in the case under discussion, $d$ is related to the coherent scattering density $N_B$ of the mirror material by (7):

$$ \frac{1}{d} = \left[ 2\pi N_B \left(1 - \frac{\gamma^2}{\gamma_c^2}\right) \right]^{\frac{1}{2}} \quad (2.18) $$

The reflectivity coefficient $R_p$ of a film of thickness $t$ is given by

$$ R_p = 1 - \exp \left(-\frac{2t}{d}\right) \quad (2.19a) $$

$$ = 1 - \exp \left(-\frac{4t}{N_B} \left(1 - \frac{\gamma^2}{\gamma_c^2}\right)^{\frac{1}{2}} \right) \quad (2.19b) $$

and is plotted in Figure 5 as a function of $(\gamma/\gamma_c)$ for a nickel film of thickness $t = 1000 \lambda$. This film thickness gives a reflectivity $R_p > 98.5\%$ at all incident angles $\gamma < 0.98\gamma_c$ and this is considered to be a satisfactory film thickness for guides manufactured from evaporated nickel on to glass.

ii) Microscopic surface defects

Such defects, in distinction to macroscopic surface defects, are due to step discontinuities in the surface caused by atomic dislocations, grain boundaries or crystal plane slips. If we consider the mirror surface to deviate positionally from the ideal surface by $\pm \varepsilon$, then this causes an optical path difference $\phi = 8\pi\varepsilon \sin \gamma_c/\lambda$, and a phase difference (7)

$$ \phi = 8\pi\varepsilon \sin \gamma_c/\lambda \quad (2.20) $$

between the neutrons scattered at the $+\varepsilon$ and $-\varepsilon$ local planes. The resulting reflectivity becomes

$$ R_{\text{Mic}} = 1 - \frac{\phi^2}{4} \quad (2.21) $$

$R_{\text{Mic}}$ is 0.99 for defect amplitudes $\varepsilon = 5 \lambda$. As $\varepsilon$ is much less than the minimum penetration depth $d = 93.6 \lambda$ at $(\gamma/\gamma_c) = 0$ in equation (2.18) for reflection from nickel this effect is much less important than the other loss mechanisms.

iii) Macroscopic surface defects

Macroscopic defects due to a physical roughness or waviness of the reflecting surface can cause a significant impairment of the effective reflectivity, since they can cause the local incident angle to become greater than $\gamma_c$. A good estimate of the magnitude of any waviness can be obtained by optically measuring single reflections, and such measurements have been used as a criterion for selecting glass for neutron guides (see Section 4a). The effect of surface waviness for single neutron reflections can be considered by giving the reflection point a local slope with a FWHM of $\Delta\alpha$. For a straight guide the reflectivity decrease $\delta R_{\text{Mac}}$ per reflection is $\approx (\Delta\alpha/2\gamma_c)$ and for a 2-wall guide of length $L$ and separation 'a' the total macroscopic reflectivity loss is approximately given by

$$ \frac{\delta R_{\text{Mac}}}{R} \approx \frac{\Delta\alpha}{4} \frac{L}{a} \quad (2.22) $$

ie, this loss is independent of the wavelength at least for $\Delta\alpha << \gamma_c$.

This expression cannot however explain the losses in a real guide since it assumes that successive reflections are co-planar, and this will not generally be the case. The losses due to surface waviness in real guides are best calculated by Monte Carlo simulation where each neutron trajectory is followed individually.
The magnitude of the surface waviness of the glass used in neutron guides should be less than $10^{-4}$ rads, which is ~1% of the critical glancing angle of $3\times$ neutrons on nickel.

iv) Reflectivity losses due to imperfect mechanical construction

Neutron guides are best fabricated by evaporating ~1000 $\AA$ of nickel onto high quality finish glass plates which are then assembled in straight lengths to form rectangular cross-section conducting tubes. Curved guides are realised by mutually orienting individual short straight lengths of guide to the required curvature. This method of construction introduces the following loss mechanisms:

1 Imperfect spatial alignment

If individual sections of a longer guide are misaligned at their ends by an amount $\Delta a$ in the horizontal plane than the loss in transmission is $\sim \Delta a/a$ per section, where 'a' is the guide dimension. A similar loss can occur for any vertical misalignment. Thus in order to reduce losses at each abutment to below 0.1%, $\Delta a < 0.0005a$. As an example, in a 5 cm square guide composed of 30 one metre long sections, a must be less than 25 $\mu$m in order to reduce losses by this mechanism to below 3%.

2 Gaps between sections

These losses are proportional to the ratio between the gap and the lengths of the individual short guide sections. A typical gap ~0.1 mm between adjacent plates thus introduces a 0.1% loss in a 1 m section of guide plate. This enables the guide to be designed to allow for thermal expansion.

3 Imperfect angular alignment

Imperfect angular alignment has the same effect as macroscopic surface distortions. Whereas the latter vary randomly, the former imposes a systematic variation $\Delta a_2$ to the reflection angles. Again the effect is best calculated by computer simulation. In general any angular misalignment should be within the variation in surface waviness ie $10^{-4}$ rads.

4 Losses in curved guides due to the polygonal approximation

In approximating curved guides by short straight sections - the polygonal approximation - each section must be sufficiently short so that its orientation $\Delta a_3$ with respect to the next section is not greater than the surface roughness. It can be shown that the number of straight sections required for a 'line of sight' circularly curved guide is

$$N = \left(\frac{\lambda^*}{\Delta a_3}\right)^2,$$

(2.23)

since $\Delta a_3$ is then the maximum angular misalignment. If we set $\Delta a_3 = 10^{-4}$ rad, which is equal to the surface waviness, we obtain $N \approx 18$ for a 'line of sight' guide where $\lambda^* = 1 \AA$, and $N \approx 108$ for a 'line of sight' guide where $\lambda^* = 6 \AA$. 'Line of sight' guides with longer characteristic wavelengths have smaller radii of curvature and hence require a larger number of straight elements to approximate to a true circle.

(c) Guide Illumination

The moderator areas at reactor sources 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 (see Section 4) 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 6. 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 $L_1$, and the guide exit to sample distance is $L_e$. In all cases of practical importance $m > g > s$. The condition $g > s$ generally pertains for pulsed sources due to time-of-flight resolution requirements.

Illumination matching of the guide at a particular wavelength $\lambda$ 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 $\gamma_c$ for that wavelength. Illumination matching of the sample follows the same behaviour. For nickel guides ($\gamma_c = 0.0017 \text{ rad} \cdot \lambda^{-1}$), the matching conditions are expressed as follows:

$$0.0017\lambda = \frac{(m-g)}{2L_1}, \quad \text{and} \quad 0.0017\lambda = \frac{(g-s)}{2L_e}$$

(2.24)

(2.25)

and these relationships are plotted in the $(g - \lambda)$ diagram shown in Figure 7. Point M represents the matching of the complete moderator-guide-sample system at the matched wavelength $\lambda_M$.

The illumination conditions in the numbered areas of the $(g - \lambda)$ diagram are as follows:

Region 1: Completely illuminated guide* Completely illuminated sample†

Region 2: Completely illuminated guide Incompletely illuminated sample

Region 3: Incompletely illuminated guide Completely illuminated sample

Region 4: Incompletely illuminated guide Incompletely illuminated sample

In region 1 the gain $G$ of a guide over a non-reflecting collimator at its exit plane is proportional to $\lambda^2$, as expressed in equation (2.7). This gain holds up to a maximum wavelength $\lambda_M$. At longer wavelengths the gain factor continues to increase up to a saturation wavelength $\lambda_s$ 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. This is illustrated in Figure 8. $\lambda_s$ defines the wavelength at which no further gains ensue. This effect is demonstrated in curve B of Figure 9 where the results were obtained by the Monte Carlo simulation method to be described in section 2d. For the completely matched condition (point M in Figure 7) a ray diagram can be drawn in which the guide contracts into one line; this is shown in Figure 10. In any practical situation $m$ is fixed by the source (e.g. $m \sim 10 \text{ cm}$ for a moderator on the Rutherford Laboratory spallation neutron source), $s$ is fixed by instrument resolution requirements and $\lambda_{\text{max}}$ 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 $(L_1 + L_e)$, 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 10 for either fixed $L_1$ or fixed $L_e$.

Equations (2.24) and (2.25) may be combined to give the complete matching condition

$$\lambda_M = \frac{294}{(m-g)+(L_1+L_e)}$$

(2.26)

for nickel guides.
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.

It is clear that instrumental design factors might well determine the longest \( \lambda_{\text{M}} \) which is achievable in any given situation. These figures show that it would be very difficult to design a matched system at wavelengths \( \lambda > 6 \AA \) since there is a minimum practicable moderator-guide entrance distance \( \approx 2 \) m.

We shall now consider the intensity distribution at the sample for a fully illuminated sample configuration. All neutrons of wavelength \( \lambda \) emerging from the guide are contained with a solid angle \( \Omega_c = 4\gamma_c^2 = 4\lambda^2\pi/N \) and for straight guides they form image planes close to the guide exit which contain well-defined umbral and penumbral regions. The intensity distribution across the sample plane is thus, in general, trapezoidal. We have considered in some detail the intensity distribution from a square guide (linear dimension \( g \)) at a sample plane placed at a distance \( L_e \) from the guide exit. This distribution may be obtained by considering a two-dimensional convolution of a square, sides \( g \), and a smaller square, sides \( b \), where \( b = 2\gamma_e L_e \) and is wavelength dependent. The resulting shape approximates to the truncated "pyramid" illustrated in Figure 11. We may utilise the calculated partial volumes from various regions of the "pyramid" to estimate the percentage of neutrons leaving the guide that reach the sample. The flat region above the \((s \times s)\) area represents the umbral region. The partial volume above a square with sides \((s + 2a)\) symmetrically positioned is:

\[
\text{Partial Volume} = \left[ s + 2a(1 - \frac{a}{2b}) \right]^2, \quad \text{if } a < b. \tag{2.27}
\]

The total volume of the truncated pyramid is:

\[
\text{Total Volume} = (s + b)^2 = s^2. \tag{2.28}
\]
The differential neutron flux* at the guide entrance in the fully illuminated region I of Figure 7 is equal to \( \phi_m \), the differential neutron flux at the moderator surface. For a perfect guide the differential neutron flux at the guide exit is also equal to \( \phi_m \) and is contained within a solid angle \( \Omega_t \). The integrated intensity at the guide exit is therefore given by

\[
I_g = \phi_m \Omega_t s^2 \text{ ns}^{-1}
\]

(2.29)

and the general expression for the integrated intensity at a sample of size \((s + a)^2\) becomes

\[
I_s = \phi_m \Omega_t \left[ s^2 + 2a \left( 1 - a/2b \right) \right] \text{ ns}^{-1}
\]

(2.30)

This expression holds only for \( a < b \) where \( b \) is neutron wavelength dependent and is given by \( b = 0.0034 \lambda L \). The flux on the sample within the umbra is simply \( \phi_m \Omega_t \text{ (ncm}^{-2}\text{s}^{-1}) \) and is uniform over the sample area.

(d) Computer Simulation

The basic theory described in Section 2a has been used to write a code which simulates the behaviour of guides. This code was required since it is only in the case of continuous straight guides that analytical expressions give an adequate description of guide properties. The present Monte Carlo code (MCGUIDE) attempts to quantify the effects present in a real (ie imperfect) three-dimensional guide and a full description will be found elsewhere(8). The effects incorporated in the code are:

- a finite sized moderator, which may be inclined to the guide axis
- a 3-d guide constructed from up to 100 segments.

The code MCGUIDE has been tested against the measured transmission of a 48 m section of the 144 m guide at Garching(9). In this measurement Au foils were placed 48 m apart beyond the line of sight of the source, and their relative activations measured for a series of neutron wavelengths. The experimental results are shown in Figure 12 as dots. The corresponding calculations using MCGUIDE are shown as crosses. It will be seen that, except at low wavelengths, the transmission is constant and well matched by the calculation.

3 APPLICATION TO PULSED SOURCES

(a) General Considerations

1) Matching of source and guide solid angles

The intensity losses incurred in guide tube installations on continuous reactor sources due to the mismatching of the solid angle of acceptance
of the guide and the solid angle subtended by the neutron source at the guide entrance can be appreciable, particularly towards longer wavelengths. On a pulsed source, where the effective moderator face area is likely to be much smaller and much more well defined that the large diffusely defined region around a reactor core, the necessity to match the guide with the moderator is of paramount importance. This is an important practical difference between guides on continuous and pulsed sources and has been discussed in Section 2c.

Monte Carlo simulations have been used to predict the intensity transmitted by two typical guides at a given wavelength as a function of the moderator-guide entrance separation $L$. The shape of the curve in Figure 13 illustrates the principle of matching, and is a simulation of the behaviour of the 'IRIS spectrometer guide (Section 3c) when transmitting $6.5 \bar{R}$ neutrons. Similar curves for the HRPD (Section 3b) are shown for a series of wavelengths in Figure 14. It can be seen that it is necessary, especially at long wavelengths, for the guide entrance to be close to the moderator in order to exploit fully the potential gains of guides.

As an illustration of this point we show in Figure 9 the calculated intensities transmitted by a perfect straight guide to a position 12 metres from the moderator as a function of wavelength for different moderator-guide entrance distances $L$. These results are also valid for longer guide lengths. Total illumination occurs at all wavelengths $\lambda < \lambda_{\text{m}}$ and in this wavelength range the transmitted intensity rises in proportion to $\lambda^2$ as predicted by equation 2.7. The saturation condition is signified by the onset of a plateau in the intensity curve. Note that as $L$ increases then the intensity at saturation is reduced considerably. This would be an important point to consider should there be plans to exploit the SNS as a source of ultra cold neutrons.

ii) Converging guides

Converging guides (neutron funnels) can be used to provide useful intensity gains which increase with the neutron wavelength. Figure 15 shows that a 9 m funnel whose entrance is 3 m from the moderator transmits higher intensities beyond $20 \bar{R}$ than the straight guide placed 2 m from the moderator (Curve B of Figure 9). Funnels can also be useful at shorter wavelengths ($\lambda < 4 \bar{R}$) where gains $\sim 25\%$ over a straight guide are predicted (Figure 16, Curve A). However if the funnel is the first section of a guide system which includes straight sections, then the gain achieved by using the funnel can be nullified (Figure 16, Curve C). The use of a funnel for thermal neutrons ($\lambda < 4 \bar{R}$) can only really be advantageous when there is a continuous tapering to the sample.

Guide funnels are likely to be more useful between guide exits and sample positions. If the angle of the funnel with respect to the guide axis at its exit is $\gamma_{\text{f}}$, as shown in Figure 17, then this gives appreciably enhanced fluxes at the corresponding wavelength $\lambda_{\text{m}}$ (equation 2.6) in the umbral region at the sample compared to the case with no funnel. The effect of the funnel is to reflect neutrons from the penumbra in the no-funnel situation, into the umbra in the case of the funnel. The optimisation of the geometry of a converging guide will in general be best carried out using a Monte Carlo procedure as discussed in this report. A particular advantage of this arrangement at the guide exits of pulsed source instruments is that it could provide a method for improving the time-of-flight resolution by having a smaller sample size, but with only a modest loss in total intensity.

iii) Path length uncertainties

The reflections in guides introduce an extra flight path uncertainty $\Delta L$ along a guide of nominal length $L$ which is not present in a non-reflecting collimator. For zig-zag reflections down straight and curved guides, to first order

$$\Delta L_{\text{max}} \approx \frac{\gamma_{\text{c}}^2}{L}$$

(3.1)

whereas for garland reflections down a curved guide:
The effect can be neglected in all foreseeable applications, and only reaches 1 part in $10^4$ for a neutron wavelength of 8.3 Å.

iv) Beam Divergence and Q-Resolution

The inherent range of neutron solid angles accepted by the guide entrance will also be present at its exit (in contrast to the non-reflecting collimator case) and may even be increased if converging guides are employed. The maximum angular deviation of a neutron emitted by a straight guide after reflection is, for nickel surfaces, 0.1 degrees per Ångstrom. This deviation is relatively large and for certain spectrometers, particularly those operating at long wavelengths and small angles of scattering, the uncertainty in momentum transfer due to the incident beam divergence at the sample can be dominant and perhaps negate the benefits of a guide.

v) Beam Asymmetry

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 $\lambda < \lambda^*$ 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:

$$T = \cos^{-1}\left(\frac{1 - \gamma_c^2/2}{1 - (\gamma \gamma^*)^2/2}\right) \gamma_c = \left(1 - f(\gamma^*)^2\right)^{1/2},$$ (3.3)

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

$$f = \text{fractional distance across the guide exit aperture measured from the outer wall.}$$

The variation of $T$ with $f$ at various values of $\lambda/\lambda^*$ is shown in Figure 18.

One possible method for reducing this asymmetry is to include 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 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 will be 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 that 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 19 where the transverse distributions of neutrons with $\lambda = 1.0$ Å in a 8 cm x 2.5 cm guide have been plotted at 70 m, 80 m, 90 m and 100 m along a curved/straight guide system. In this system 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 that is of
prime importance. This can be 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 investigated using the MCGUIDE code for a number of configurations and will be discussed in section 3b.

vi) Guide Bunching

Since neutron guides will generally be used on the longer instruments (L > 40 m), a number of guides can be grouped together with a small angular separation within a single beam segment, and still preserve a reasonable distance (say ~ 2 m) between adjacent beam lines and instruments. This has obvious advantages in maximising the utilisation of the available neutron source.

The questions to be answered in the design of such guide bunches are:

- How many guides can usefully be included in a single beam port?
- What are their dimensions?
- Is there any adverse effect on the performance of an instrument if its guide is one of a bunch?

The constraints to be included in the design of a bunch are:

- The location and size of the window at which the guide bunch would start, (eg 24 cm x 24 cm at 3.8 m from the SNS moderator).
- The inclusion of beam choppers.
- The types of instruments that need to be served by a guide bunch.

Instrument-guide separation considerations alone suggest that up to three guides could be accommodated within a single guide bunch. This is because the maximum divergence of the guides is determined by the size and location of the window through which the guide bunch views the moderator. Beam shutter considerations at the SNS limit this window to 24 cm and its location to 3.8 m from the moderator. Using the 3-guide scheme shown in Figure 20 the distance between adjacent guide centres is:

\[ 12 - (a + c)/4 \text{ cm (at 3.8 m)} \] (3.4)

which results in the following guide-guide separations (in metres) at 40 and 100 m:

<table>
<thead>
<tr>
<th>Mean Guide Size ( (a+c)/2 ) (cm)</th>
<th>Guide-Guide Separation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distance = 40 m</td>
</tr>
<tr>
<td>2</td>
<td>1.25</td>
</tr>
<tr>
<td>3</td>
<td>1.10</td>
</tr>
<tr>
<td>4</td>
<td>1.05</td>
</tr>
<tr>
<td>5</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 2 Guide-guide separations at 40 m and 100 m for the guide width parameters 'a' and 'c' (Figure 20).

These figures are calculated assuming the guides to be straight, and are still approximately valid for curved guides since the deflections due to curvatures appropriate to \( \lambda \approx 1 \AA \) are small compared to those produced by the angular separation. This separation appears to be adequate if the length of the guide is \( \approx 100 \text{ m} \), or if the sample-analyser-detector arrangement is sufficiently asymmetric to accommodate a \( \approx 1 \text{ m} \) separation at a distance \( \approx 40 \text{ m} \).

Guide bunching will however influence the size of any disc chopper that may be inserted between sections of the guides, and this now will be considered. Instruments with primary flight paths in the range 40 - 100 m will invariably require some form of wavelength limiting, or pulse eliminating chopper. The most efficient design for such purposes is the counter rotating disc chopper shown in Figure 21. The efficiency \( E \) of this chopper is related to the disc radius \( r \), for operation at 50 Hz, by
$E = 1 - \frac{w}{2\pi \Delta t}$ \hspace{1cm} (3.5)

where $w$ is the guide aperture and $\Delta t$ is the open time. For example, for $\Delta t = 1000\mu s$, $w = 2.5$ cm and $r = 16$ cm the counter-rotating disc chopper efficiency is $E = 0.75$. The efficiency of the disc chopper can be improved by providing as large a radius disc as possible. The proximity of nearby guides does however limit the radius which may be employed (Figure 22). This limiting radius is obtained from the expression:

$$r_{\text{max}} = \frac{(c - \frac{3}{2} - d)^2}{2(h + d)} + \frac{(h + d)}{2}$$ \hspace{1cm} (3.6)

Assuming $a=2.5$ cm, $d = 2$ cm, $h = 8$ cm, the value of $c$ (at 5 m) for a bunch of three horizontal guides is 14.1 cm. This leads to a value of $r_{\text{max}} = 11$ cm, $r_{\text{mean}} = 7$ cm (the radius at the beam centre), and a corresponding mean efficiency of 43%. This is obviously unacceptable.

However, by lifting the centre guide in Figure 20 out of the horizontal plane (see Figure 23) it is possible to have a disc with $r_{\text{max}} = 36.3$ cm and a maximum efficiency $E = 88%$.

We therefore suggest the use of the layout shown in Figure 23 for bunching guides. This has two 'prime' guides in the horizontal plane and a further guide inclined upwards at an angle of $\approx 10^\circ$ to the horizontal. The window in the shutter is now higher than for the case discussed in Figure 20.

(b) The High Resolution Powder Diffractometer (HRPD) Guide

The High Resolution Powder Diffractometer requires neutrons in the range $\approx 0.7 \AA$ to $\approx 10 \AA$, and it was important to answer two fundamental questions before carrying out detailed calculations on optimising the guide size, curvature etc:

i) Over what $\lambda$ range would a practical guide system transmit neutrons?

ii) Would such a guide provide a better flux than no guide at all?

The answer to the first question is provided by the measured performance of a guide built to transport neutrons over this wavelength range. The 144 m guide at Garching has $\lambda^* = 0.7 \AA$, and measurements of the transmission in the range $1 - 7 \AA$ indicate that, within this wavelength range, the losses over a 100 m guide are essentially constant and approximately 40%. Below $1 \AA$ the losses will increase progressively and powder profiles recorded using an Al$_2$O$_3$ sample reveal that the useful lower limit of the wavelength range is $\approx 0.7 \AA$.

The usefulness of a guide is also apparent if we calculate the 'cross-over' wavelength above which a guide out-performs a simple collimator. This is given by (cf equation 2.7).

$$\lambda_c^2 = \frac{A}{4L^2cT}$$ \hspace{1cm} (3.7)

where $A$ is the area of the moderator, $L$ is the moderator-sample distance, $c$ is the term in the expression $\gamma_c = c\lambda$ and is 0.0017 mrad $\AA^{-1}$ for Ni guides, and $T$ is the transmission of the guide.

For the values appropriate to this instrument (viz $A = 100$ cm$^2$, $L = 100$ m, $c = 0.0017$) $\lambda_c$ is 0.38 $\AA$ for a transmission of 60%. Even for a guide transmission of only 20% the cross-over wavelength $\lambda_c$ is 0.65 $\AA$ and there is a clear advantage in using a guide for neutrons in the range $\lambda > 0.7 \AA$. The elements of a possible guide system are shown in Figure 24. The guide consists of three principal sections:

i) A straight section from the beam shutter to the outside of the biological shield (a to b in Figure 24). This section is straight to facilitate construction within the shield.

ii) A circularly curved section to remove fast neutrons (from b to c, Figure 24).

iii) A straight section to mitigate the beam asymmetry introduced by the curved section (c to d, Figure 24).
Each of these sections will have the same cross-sectional area, thus the geometrical parameters to be optimised are:

- the guide height \(h\),
- the guide width \(w\),
- length \(a\) to \(b\) \(L_1\),
- length \(b\) to \(c\) \(L_2\) (and hence the length \(c\) to \(d\), since the overall length \(a\) to \(d\) is fixed by resolution requirements),
- radius of curved section \(b\) to \(c\) \(R\).

The factors affecting the choice of these parameters are:

i) To reduce the number of reflections suffered from \(a\) to \(d\) the cross-sectional parameters \(w, h\) should be as large as possible.

ii) To provide complete illumination of the guide the dimensions \(w, h\) should be \(\sim w' \sim h\) where \(w', h\) are the width and height for the matched condition (equation 2.24).

iii) The characteristic wavelength \(\lambda^*\) should be in the range

\[0.2 < \lambda^* < 0.7 \ \text{m (say)},\]

since the guide's transmission decreases rapidly at wavelengths \(\lambda < \lambda^*\). For a curved guide \(\gamma^* = 4a/L_0\)

\((L_0 = \text{direct line of sight}),\) thus \(a/L_0\) should be in the range

\[8.5 \times 10^{-5} < a/L_0 < 29.8 \times 10^{-5}.\]

iv) \(L_{cd}\) should be \(> L_s\) where \(L_s\) is some minimum characteristic length \((L_s = L_s (w, \lambda))\) which decreases the asymmetry of the beam to an acceptable level.

v) To increase the transmission of the rotors necessary for wavelength selection \(w\) should be as small as possible.

vi) To provide complete illumination of the sample the dimensions \(w, h\) should be \(w > w_{ms}, h > h_{ms}\) where \(w_{ms}, h_{ms}\) are the sample-matched values (equation 2.25).

The length \(L_1\) from \(a\) to \(b\) is simply determined from the thickness of the biological shield, since there is no advantage in increasing \(L_1\) unduly. At the SNS we may therefore take \(L_1\) to be 2.7 m \((\sim 6.5 \text{ m} - 3.8 \text{ m})\).

We next consider the guide height. There are essentially only 2 conflicting factors in the choice of this dimension (i) and (ii) in the preceding list) since the guide height will certainly be large enough for complete sample illumination (point (vi)). We may therefore apply the analysis outlined in Appendix I which includes details of the optimisation of the height parameter. The value obtained is 8 cm.

This leaves two parameters, the width \(w\) and the length of the straight section \((L_s)\) to be determined. The effect of item (v) is small (a few percent) and will be ignored for the present. The two strongly competing factors are items (iii) and (vi). To provide good illumination of a \(\sim 1.5 \text{ cm}\) sample obviously requires a guide width, \(w > 2 \text{ cm}\).

However, an increase in \(w\) implies a longer characteristic wavelength with a consequential loss of intensity of the shorter wavelengths. In order to keep \(\lambda^*\) as low as possible, the line-of-sight \((a \text{ to } c\) in Figure 24) must be kept as large as possible and thus the first requirement is to find the shortest possible length \((c \text{ to } d, \text{Figure 24})\) in which the asymmetry of the beam may be removed.

In order to study the beam asymmetry as a function of \(L_s\) (and \(w\)) the following simulations were performed using MCGUIDE. Three guide widths were chosen \((w = 2.0, 2.5 \text{ and } 3.0 \text{ cm})\) and for each width a radius was chosen so that line-of-sight occurred at the end of a 60 cm curved section. The guide parameters were as follows:

<table>
<thead>
<tr>
<th>(w(\text{cm}))</th>
<th>(R(\text{km}))</th>
<th>(\lambda^*(\text{m}))</th>
<th>(L_0(\text{m}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>22.5</td>
<td>0.78</td>
<td>60</td>
</tr>
<tr>
<td>2.5</td>
<td>18.0</td>
<td>0.98</td>
<td>60</td>
</tr>
<tr>
<td>3.0</td>
<td>15.0</td>
<td>1.18</td>
<td>60</td>
</tr>
</tbody>
</table>

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 $w = 2.5 \text{ cm}$ are shown in Figure 25 for
$
\lambda = 0.6, 0.8, 1.0, 1.2, 1.4, 1.6 \text{ \AA}.
$
This illustrates that 'nodes' occur in the intensity distributions and that as $\lambda$ decreases, the straight section must be longer for equalisation of the beam. From the results shown in Figure 25 it would appear that a final straight section of length 35 - 40 m would prove adequate.

Similar results were obtained for the guide with a width of 2 cm except that, as expected, the narrower guide required a shorter $L_s$ ($\sim 25 \text{ cm}$) to achieve an acceptable equalisation of the beam. The larger width ($w = 3.0$) did not produce an acceptable beam profile even at $L_s = 40 \text{ m}$ and this, combined with the higher $\lambda^*$, which results in a comparative loss of intensity below 1 \text{ \AA} - rules out the use of a guide of this size.

The beam asymmetries and relative intensities calculated for two guide systems with the geometrical parameters described in Table 3 are illustrated in Figure 26 as a function of wavelength. It will be seen that the wider of the two guides provides a higher flux at the sample above $\lambda = 0.9 \text{ \AA}$ and has a marginally better beam symmetry. Guide A was therefore selected for further study.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Width $w$</td>
<td>2.5 cm</td>
<td>2.0 cm</td>
</tr>
<tr>
<td>Height $h$</td>
<td>8 cm</td>
<td>8 cm</td>
</tr>
<tr>
<td>Position $a$</td>
<td>3.8 m</td>
<td>3.8 m</td>
</tr>
<tr>
<td>Position $b$</td>
<td>6.5 m</td>
<td>6.5 m</td>
</tr>
<tr>
<td>Position $c$</td>
<td>60 m</td>
<td>75 m</td>
</tr>
<tr>
<td>Position $d$</td>
<td>100 m</td>
<td>100 m</td>
</tr>
<tr>
<td>Radius $R$</td>
<td>18 km</td>
<td>35.16 km</td>
</tr>
<tr>
<td>Characteristic Wavelength $\lambda^*$</td>
<td>0.98 \text{ \AA}</td>
<td>0.63 \text{ \AA}</td>
</tr>
</tbody>
</table>

Table 3 Design parameters of two possible guides for the HRPD. The positions refer to distances from the moderator.

The High Resolution Quasielastic Spectrometer ('IRIS) Guide

The High Resolution Quasielastic Spectrometer operates on the principle of selecting the incident neutron energy by TOF, and analysing the final energy by Bragg reflection from single crystals. In order to achieve the desired resolution in the incident beam it is necessary to locate the sample 40 m from the moderator. The final neutron energy is selected with high resolution by sets of pyrolitic graphite and silicon crystal analysers in exact backscattering. The values of the final energies are 2.07 meV ($\lambda = 6.69 \text{ \AA}$) and 1.82 meV ($\lambda = 6.28 \text{ \AA}$) respectively. The spread of incident energies is limited to $\pm 1 \text{ meV}$ ($\lambda \leq 2 \text{ \AA}$) in order to prevent overlap of successive neutron pulses. Therefore the instrumental requirements are that the incident beam will not, in general, consist of neutrons of wavelength less than 4 \text{ \AA}.

Because of its high resolution 'IRIS is a comparatively low count rate spectrometer and therefore in designing the guide maximum transmission was a prime consideration. Thus the matching condition at $\lambda = 6.28 \text{ \AA}$ was taken to be the dominant factor in calculating the guide aperture. The first component in the spectrometer, a fast chopper at 2.1 m from the 10 x 10 cm$^2$ moderator has determined the position of the guide entrance at 2.35 m. Applying the principles of Figure 10 to the case of 6.28\text{ \AA} neutrons with $L$ defined as 2.35 m, the guide aperture for matching at $\lambda = 6.28 \text{ \AA}$ becomes 5.0 x 5.0 cm$^2$. A straight section of guide of length 1.3 m after the chopper is positioned within the neutron beam shutter. This guide will be fabricated from suitable metallic mirrors in order to minimise radiation damage (section 4b). The beam shutters and hence the guide can be located to an accuracy of 0.1 mm. A gap of 25 cm follows which is needed for the windows in the target station containment vessel, and a second straight guide of aperture 5 x 5 cm$^2$ and length 3.8 m continues beyond the edge of the biological shield. A disc chopper is located 8 m from the moderator which requires a further gap in the guide of $\sim 10 \text{ cm}$. The radiation levels are such that it should be possible to make the second straight section of guide (which starts at 3.9 m from the moderator) from nickel-plated glass without incurring radiation damage problems.
Since 'IRIS' is a low count-rate spectrometer it follows that the background must be kept as low as possible. For this reason a 'line of sight' curved guide is chosen to conduct the neutrons from the disc chopper to the entrance of the analysing section of the spectrometer, a distance of 30.1 m. From equation (2.11), where \( a = 5 \text{ cm} \), this gives a radius of curvature of \( \approx 2.3 \text{ km} \). The corresponding characteristic wavelength \( \lambda^* \) of the guide is \( 3.91 \text{ Å} \) and this ensures that the beam asymmetry at the guide exit is tolerable for neutron wavelengths near the analysing wavelengths for the two sets of crystal analysers. The displacement of the axis of the guide exit from the straight through position is 20 cm which allows a reasonable separation of the monochromatic beam from the main beam.

A second disc chopper is situated at the exit of the curved guide and is used for eliminating neutrons scattered directly into the detectors. This disc requires a gap of 10 cm and is followed by a converging guide of length 1.5 m with a taper angle equal to the critical angle at \( \lambda = 5.9 \text{ Å} \). This focusses neutrons on to the sample position. Small samples must be used on 'IRIS' in order that the resolution of the instrument is not degraded by sample size effects. This means that, particularly in the high resolution option, a converging guide is necessary to maximise the flux on the sample. The divergence of the beam is approximately doubled by the use of a nose. This divergence does not affect the performance of the spectrometer which will be used for experiments requiring relatively coarse angular definition (Q-resolution). The relative fluxes (normalised to the no guide situation) and transmitted to the sample are given in Table 4 for different guide geometries. These figures were obtained using the MCGUIDE program \(^8\).

The tapered guide at the exit of the guide system has yet to be optimised but it is envisaged that a number of interchangeable tapered guides will be available to suit the sample geometry. A surface roughness of \( 10^{-4} \text{ rads} \) has been assumed in the simulations. A schematic diagram of the spectrometer and its guide system is shown in Figure 28.

<table>
<thead>
<tr>
<th>CONFIGURATION</th>
<th>Relative Fluxes (Normalised to Case (i))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \lambda = 6.29 \text{ Å} )</td>
</tr>
<tr>
<td>(i) No guide</td>
<td>1</td>
</tr>
<tr>
<td>(ii) Continuous Perfect Straight Guide</td>
<td>76.9</td>
</tr>
<tr>
<td>(iii) Real Curved Guide</td>
<td>47.1</td>
</tr>
<tr>
<td>(iv) Case (iii) with 1.5 m 1-D tapered guide (sample size 5 x 2 cm(^2))</td>
<td>74.3</td>
</tr>
<tr>
<td>(v) Case (iii) with 1.5 m 2-D tapered guide (sample size 2 x 2 cm(^2))</td>
<td>100.5</td>
</tr>
</tbody>
</table>

Table 4 Relative fluxes calculated for different 'IRIS guide geometries.

4 PRACTICAL ASPECTS OF GUIDE CONSTRUCTION

The best reflecting surface for neutron guides is nickel-coated glass. Glass provides the best possible surface quality and nickel has a very high critical angle per unit wavelength. A guide assembly consists of individual plates of highly polished glass which are joined together so as to minimise the mechanical alignment losses described in Section 2. Figure 29 shows the cross-section of a standard ILL guide where each 'element' is 1 m long. The four glass plates are glued together to form the rectangular cross-section before the final alignment, and the entire space within the steel casing is evacuated.

It may be preferable to use polished metal mirrors rather than glass in certain guide sections in spite of their lower reflectivities. Examples
where this may be desirable are in high neutron fluxes close to the
source where highly borated glass tends to disintegrate due to
$^{10}\text{(n,}\alpha)^7\text{Li}$ processes, or where it is required to install guide
sections in moving instrument components such as shutters or mechanical
velocity selectors.

(a) Garching Guide for TOF Powder Diffractometer (10)

This guide is 144 m long, and details of its construction were discussed
with E Steichele at Garching since it was designed to have high trans­
mittances in the more difficult short wavelength range ($\lambda < 1 \mu \text{m}$) and
it is the nearest equivalent guide to that required for the SNS high
resolution powder instrument. The most important points arising from
this discussion are listed below:

i) The surface waviness of each 1 m long glass section was individ­
ually measured using a penta-prism before nickel evaporating and
fabricating the guide tube. The glass was selected for use if the
total waviness as observed by this optical measurement was less
than $10^{-4}$ rad.

ii) The lengths of glass were cut after glueing a strengthening
section near the ends, nickel evaporated, and then glued using
a special jig to define the guide aperture height and ball
bearings (diameters $\approx 25$ mm) to define the guide's channel
width.

iii) The 1 m sections were joined in groups of 12 using metal lugs;
these were placed on an aluminium tray and introduced into a
12 m long steel tube. The alignment of each 1 m section was
achieved by using four adjusting screws (a pair at one end of a
vertical plate, and one at each end below the lower plate) which
were tightened against springs to prevent the relaxing steel from
breaking the glass.

iv) The 12 m long steel sections were joined using rubber inserts to
allow for the $\approx 70^\circ$ angle between adjacent tubes. The steel
pipe contained transparent windows separated by 1 m to allow a
theodolite alignment of the individual sections in the horizontal
plane. There were also access points in the steel casing at
selected points near the guide section abutments to facilitate
gold foil measurements of the fluxes transmitted down the guide.
The guide height was adjusted using the lower pair of screws and
a spirit level.

v) Pieces of boron and lead shielding, each $\approx 50$ mm long, were placed
outside the glass guide and inside the steel tube at 12 m inter­
vals down the whole length of the guide.

vi) The 12 m steel tubes were supported on concrete pillars separated
by $\approx 6$ m, and embedded $\approx 1.5$ m below ground.

vii) Guide expansion was compensated by using a special sliding
mechanism on the pillars.

viii) The entire guide length was temperature controlled to $25 \pm 3^\circ\text{C}$.

b) Radiation Damage in Neutron Guides

Towards the latter part of 1978, the ILL reported that several of the
early sections of both their thermal and cold neutron guides had been
damaged. This damage was attributed primarily to $\gamma$ emission resulting
from neutron absorption by $^{10}\text{B}$. The ILL are currently investigating
the possibility of decreasing the boron content of the glass used in
their guides (presently $\approx 12$ to 19 mole % $\text{B}_2\text{O}_3$) with the aim of easing
this problem. Accelerated irradiation tests on different glass
specimens are currently under way. The main function of the boron in
the glass used for neutron guides is to attenuate preferentially the
neutron intensity as it traverses the glass and thus limit any
problematic $(\text{n},\gamma)$ processes. $\gamma$ emission following neutron absorption
by Na in the glass effectively determines the shielding requirements
around guides.
The time-averaged neutron fluxes at the guide entrances of the SNS facility are estimated to be at least an order of magnitude lower than those at the ILL. This problem will therefore be less serious in the former. It may also be possible to use a glass for the SNS guides which has a lower B and Na content than the glass used at the ILL, and this will be investigated. Simple optical considerations suggest that the surface quality specification of the glass used in a guide is less critical in the early sections, so that this criterion can be relaxed if necessary. The effect of this relaxation will be tested by computer simulation for real guide geometries. Another possibility is to use polished Ni metal or Ni evaporated onto another polished metal for the guide sections near the source; these could then, if necessary, be backed with a borated resin sheet.

OUTSTANDING PROBLEMS

Several problems have been identified for further investigation. These may be summarised as follows:

i) The effect of fast neutron 'streaming' down the guide walls. This gives a much larger fast neutron content in the spectrum than that expected from simple optical considerations.

ii) The selection of glass for the guides, particularly the B and Na contents. The glass selected should undergo accelerated irradiation tests.

iii) The effect of using early guide sections constructed from inferior quality mirrors eg, polished metals, will be quantified by computer simulation.

iv) The method for aligning the in-shield guide sections requires detailed consideration.

v) The amount of shielding needed around the guide tubes needs quantifying.

vi) The optimum method of guide bunching requires further attention.

vii) Further calculations will be performed on the applicability of using converging guides.

viii) R Scherm (Braunschweig) has suggested that the nickel isotope $^{58}\text{Ni}$ should be reconsidered as the mirror material, since its scattering density is approximately 40% greater than that of naturally occuring nickel. Its use has been discounted in the past on the grounds of cost and availability. The isotope is available from the Oak Ridge National Laboratory in $10\text{ gm}$ quantities at an approximate cost £100 per gm. The cost of $^{58}\text{Ni}$ isotope required in a $1000\text{ Å}$ thick film for a typical neutron guide would therefore be $\sim \text{£}20$ per metre. We shall investigate the feasibility of preparing $^{58}\text{Ni}$ thin film mirrors on glass using small quantities of the metal while also minimising losses.

ACKNOWLEDGEMENTS

We acknowledge the help and advice given by Dr E Steichele (FRM, Garching), Mr K Knowles (RL) and Mr J Penfold (RL).

REFERENCES

2. E Fermi and W H Zinn, Phys Rev 70 (1946) 103.
8. M W Johnson, Rutherford Laboratory Report, to be published.

E Steichele and P Arnold, Phys Letts (1973) 165.

FIGURE CAPTIONS

Figure 1 The dependence of the reflectivity coefficient on the ratio of the angle of reflection $y$ to the critical glancing angle $y_c$.

Figure 2 The gain factor $G$ in the neutron flux transported by a straight guide over that observed in the absence of the guide over the same area, as per equation (2.2).

Figure 3 Geometric definition of line of sight $L_o$ and characteristic angle $\gamma^*$ for circularly curved guides.

Figure 4 The variation of the line of sight length $L_l$ of curved-straight guide combinations as a function of curved section length $L_c$ (both quantities are normalised with respect to $L_o$).

Figure 5 The penetration dependent reflectivity coefficient $R_p$ as a function of $y/y_c$ for $y/y_c > 0.9$.

Figure 6 Illumination matching of guide with the moderator and the sample at a wavelength $\lambda_c$ ($y_c = 0.0017 \lambda_c$ for Ni).

Figure 7 Different guide and sample illumination conditions illustrated schematically for various guide dimensions $g$ as a function of wavelength $\lambda$.

Figure 8 Geometric definition of the saturation wavelength $\lambda_s$ and the matched wavelength $\lambda_m$.

Figure 9 Calculated intensities transmitted by a straight guide terminating at 12 m as a function of wavelength for different values of moderator-guide entrance distances.

Figure 10 A ray diagram illustrating matched guide and sample illumination.
Optimisation of Rectangular Guide Cross-Sections

This section considers the optimisation of a neutron guide aperture when the two competing effects are the illumination of the guide and the guide transmission. Note that this analysis does not take sample illumination, curvature, or other effects into account.

The existence of an optimum size arises from the fact that a large guide cross-section improves the transmission of the guide by decreasing the number of reflections, but decreases the illumination of the guide by a finite sized moderator.

We first consider the losses due to the number of reflections. Rather than use an ab-initio calculation of the total reflectivity losses we will use an empirical approach based on the measured transmission of the 144 m long (14 cm x 2.5 cm) aperture guide at Garching. On this guide the transmission was found to be ~ 0.78 over a 48 m section and was independent of wavelength for \( \lambda \) over the range \( 1 < \lambda < 4 R \). Thus denoting the gross reflectivity by \( R \) and incorporating all losses by \( R^n = 0.78 \), where \( n \) is the average number of reflections we obtain:

\[
\bar{n} = \frac{Le\lambda}{2} \left( \frac{1}{w} + \frac{1}{h} \right),
\]

for a width \( w \) and height \( h \) (see equation 2.9), and \( c = 0.0017 \ \text{mrad} \ \text{R}^{-1} \) for nickel guides. For the 48 m section of the Garching guide

\[
\bar{n} = \frac{4800 \times 0.0017\lambda}{2} \left( \frac{1}{2.5} + \frac{1}{14} \right),
\]

hence \( \bar{n} = 1.93\lambda \). By setting \( 0.78 = R^{1.93\lambda} \) we obtain

\[
R = e^{-1/7.77\lambda},
\]

for this particular guide section.
The fractional illumination losses may also be calculated. Figure A1 shows a projection of the 4-d phase space diagram of transmittable neutrons at the moderator surface. In this figure only one positional and one angular coordinate is shown, and the neutrons which are not available for transmission are those from the shaded triangles DEC ($A_{DCB}$).

The phase-space volume of the unavailable neutrons from this phase is therefore:

$$2A_{DCB} 2\gamma_c w$$

(A.4)

which proves to be

$$(L \gamma_c - (m-h)/2)^2 2\gamma_c w/L_1$$

(A.5)

and similarly for the other projection

$$(L \gamma_c - (m-w)/2)^2 2\gamma_c h/L_1$$

(A.6)

(this analysis ignores cross-terms from the two projections but in practice these are small).

Hence the fractional illumination is given by:

$$I_f = 1 - \frac{[L \gamma_c - (m-h)/2]^2}{2\gamma_c L_1 h} - \frac{[L \gamma_c - (m-h)/2]^2}{2\gamma_c L_1 w}$$

(A.7)

where 
\[
{x} = \begin{cases} 
  x & \text{if } x \geq 0, \\
  0 & \text{if } x < 0.
\end{cases}
\]

This expression is easily evaluated for a series of combinations of the guide height $h$ and wavelength $\lambda$ and can be used to obtain the optimum height at a given neutron wavelength for fixed $L_1$, $L$, $m$, and $w$.

Example: for $L_1 = 380$ cm

$L = 10000$ cm

$\gamma_c = 0.0017$

$w = 2.5$ cm

and for a square guide for which $h = w$

$$I_f = 1 - \frac{(L \gamma_c - (m-w)/2)^2}{\gamma_c L_1 w}$$

(A.9)

Combining the two expressions for the transmission and illumination yields for a rectangular guide:

$$TI = \left[ \exp \left( -1/7.77\lambda \right) \right]^n \left[ 1 - \frac{(L \gamma_c - (m-h)/2)^2}{2\gamma_c L_1 h} \right]$$

(A.10)

where 
\[
{\gamma}_c = \frac{c\lambda}{\lambda} = \text{critical glancing angle for wavelength } \lambda.
\]
The following figures are obtained:

<table>
<thead>
<tr>
<th>h (cm)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>$\bar{\lambda}_{1-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>.518</td>
<td>.518</td>
<td>.518</td>
<td>.518</td>
<td>.518</td>
</tr>
<tr>
<td>6</td>
<td>.537</td>
<td>.537</td>
<td>.537</td>
<td>.531</td>
<td>.536</td>
</tr>
<tr>
<td>7</td>
<td>.551</td>
<td>.551</td>
<td>.547</td>
<td>.533</td>
<td>.546</td>
</tr>
<tr>
<td>8</td>
<td>.562</td>
<td>.560</td>
<td>.546</td>
<td>.528</td>
<td>.549</td>
</tr>
<tr>
<td>9</td>
<td>.570</td>
<td>.550</td>
<td>.537</td>
<td>.518</td>
<td>.544</td>
</tr>
<tr>
<td>10</td>
<td>.559</td>
<td>.541</td>
<td>.522</td>
<td>.503</td>
<td>.531</td>
</tr>
</tbody>
</table>

This calculation shows that the optimum height for the HRPD guide is $h \approx 8$ cm.
\[ \left( \frac{\lambda(\text{Å}) \times L(\text{m})}{m(\text{cm})} \right) \]

**FIGURE 2**
\[
\frac{L_1}{L_0}
\]

\[
F = \frac{L_c}{L_o}
\]

FIGURE 4
FIGURE 16

N.B. $\gamma_F \equiv \lambda_F = 1.33 \text{Å}$. 

<table>
<thead>
<tr>
<th>Line</th>
<th>FUNNEL</th>
<th>STRAIGHT GUIDE</th>
<th>FUNNEL + STRAIGHT GUIDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10</td>
<td>5.92 cm</td>
<td>10 5.92 cm</td>
</tr>
<tr>
<td></td>
<td>3m</td>
<td>12m</td>
<td>3m 12m 40m</td>
</tr>
<tr>
<td></td>
<td>5.92 cm</td>
<td>12m</td>
<td>5.92 cm 12m 40m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

INTENSITY AT GUIDE EXIT (arbitrary units)

WAVELENGTH Å
FIGURE 22
FIGURE 25
FIGURE 26
Figure 27

Diagram showing:
- FAST DISC MODERATOR CHOPPER
- DETECTORS
- FOCUSING GUIDE
- SAMPLE
- ANALYSERS
- R = 2.3 km
- Dimensions:
  - 38 m
  - 30.1 m
  - 8 m
  - 3.8 m
  - 2.35 m
  - 1.3 m

Not to scale.
FIGURE 28

DIMENSIONS IN mm
FIGURE A1