REPORT ON THE REPAIR OF THE OPAL NEUTRON BEAM TRANSPORT SYSTEM

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ABSTRACT

The OPAL research reactor commenced operation early in 2007, and has been in continuous operation for most of the time since then. Initial characterization measurements of the cold and thermal neutron beams that feed the neutron guide hall confirmed the high fluxes that had been predicted in the design process [1], [2]. However, by 2011 it was clear that the performance of the neutron guide system had degraded substantially. Investigation revealed that the degradation resulted from delamination of the guides. The root cause was build-up of mechanical stress in the glass substrates due to alpha radiation produced during neutron capture by boron in the glass. Remediation involved replacement of 72 metres of the neutron guide system with guides that use glass substrates which have higher radiation resistance. Neutron flux and spectrum measurements have since verified that the performance of the system has largely been restored. Preliminary measurements at the neutron spectrometers since repair reveal flux increases in the range of 40 % to 90 % relative to 2011.

1. Introduction

Modern neutron beam reactors commonly employ long and large “supermirror” guides that transport cold and thermal neutrons efficiently over 10’s of metres. Supermirrors typically consist of smooth glass plates (substrates) coated with multiple bi-layers of thin Ni and Ti films (~ 5 nm thick), which are designed to enhance the critical angle of reflection of neutrons incident on the inner surface of the guide [3]. Although the advent of supermirror guides in the 1970’s produced spectacular gains in beam transport, the technology was initially labour intensive, and therefore expensive, due to the requirement that glass substrates had to be polished to reduce surface roughness to ~ 0.5 nm or better. In the 1990’s float glass substrates [4], which achieve a naturally smooth surface in the quenching process, were shown to perform well without polishing, and consequently supermirror guides could be more affordable. New research reactors (such as FRM-II and OPAL) as well as guide upgrades at existing reactors (such as Institut Laue-Langevin) took advantage of this saving by installing large arrays of float glass supermirror guides. Problems became apparent by ~2005, when ILL identified systematic failures where float glass guides had been exposed to high fluences of thermal and cold neutrons. Subsequent irradiation tests at ILL on float glass substrates indicated a limiting fluence of ~3 x 10^{16} n/cm^2 for highly directional thermal neutrons [5].

2. Identification of the problem at OPAL

At the neutron beam transport system in OPAL's guide bunker, degradation of performance was first seen on ANSTO's neutron reflectometer, which uses a broad energy spectrum of neutrons transported from the cold neutron source via a 33 metre long supermirror guide. Identification of the cause of the problem required inspection of all beam lines in the neutron guide bunker during two successive reactor shutdown periods. The identification process also included opening of one cold guide and replacement of some damaged sections with spare components to confirm that in-pile components were not contributing to the loss of flux.
Figure 1 shows some of the damaged components, i.e. the exposed upstream end of the first out of pile section of the CG3 guide (Fig. 1 (a)), showing cracked and flaking glass at the entrance, (b) the view along the same (4 metre) length of guide, showing peeling multilayers, and (c) typical samples of guide fragments that were removed.

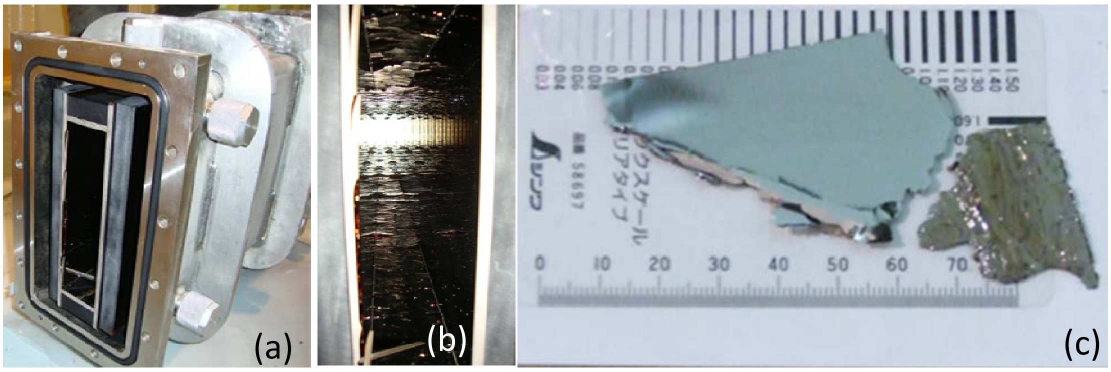

Figure 1 (a) upstream end of the removable section of the CG3 guide, showing cracks in the glass substrate on the left & upper edges, (b) view into the guide showing extensive delamination, and (c) samples of guide fragments. The right fragment is placed glass side up to reveal the layer of fractured glass that is adhered to the metal coating.

Clearly the cause of degradation was delamination of the metallic multilayer coating, along with a thin layer of float glass from the substrate of the guides. All thermal and cold guides were affected, to the extent that delamination correlated directly with accumulated neutron fluence. Referring to Table 1, we note that the radiation exposure time of TG1 and TG3 was the same because they share a primary beam shutter. The extent of damage level in TG1 is roughly twice that of TG3 because it sees twice the solid angle of neutrons. The reason there is less delamination in the cold guides is in part that the cold neutron source had been out of service for several extended periods since OPAL operations began, so they had been exposed to less radiation.

Guide	Height	Top surface	Outer curve surface	Inner curve surface
TG1	300 mm	11 ½ metres	3 metres	2 ½ metres
TG3	150 mm	5 ½ metres	1 metre	1 metre
CG1	200 mm	4 metres	No damage	No damage
CG3	200 mm	4 metres	No damage	No damage

Table 1: Distance along the guide to which some amount of delamination could be seen through the viewing ports. Distance is measured from the reactor face. All these guides are 50 mm wide.

The root cause is build-up of mechanical stress in the glass substrate due to alpha radiation produced during neutron capture by boron (B), in the following process;

$^{10}B + n_{thermal}$ -> ^{11}B (t ~ 10^{-12} sec) -> ^{7}Li (E~ 1.47 MeV) + α (E~ 0.84 MeV) + γ (E~ 0.48 MeV)

The alpha (α) particle, in particular, produces local structural damage, due to collision with neighbouring molecules in the glass. Eventually the stress reaches a critical level whereby the glass fractures under the tensile stress of the metallic coating. The evidence of the nature of the delamination, in conjunction with the observation that the extent and distribution of delamination correlates well with the flux of divergent source neutrons provides compelling evidence that the root cause of the delamination lies in structural damage to the *borofloat* glass.

Although the total length of damaged guide was 25 metres, we decided to replace 72 metres of borofloat guides with guides that have substrates that are substantially more radiation resistant to ensure at least a further 10 years lifetime of the transport system. The reason that this problem was not seen in early irradiation studies (before 2000) was that those studies exposed glass coupons to isotropic radiation, whereas in practice most of the neutrons that penetrate the glass in neutron guides (i.e. those that are not reflected at the metal interfaces) are absorbed by Boron in the first 1 - 2 mm depth of the *borofloat* glass.

The solution is to replace all *borofloat* glass substrates [4] that are in high flux areas by a glass that has substantially higher radiation resistance. The industry standard for such conditions is known as *borkron* glass. It has essentially the same neutron absorption power as *borofloat*, but can withstand over fifty times higher neutron fluence before delamination [5]. *Borkron* glass can now be polished to equivalent quality as *borofloat* glass, so no supermirror performance penalty is expected, but there is a cost penalty.

3. The guide replacement program

Repair required replacement of roughly ½ of the in-bunker neutron guide system. This involved an extensive period of manufacturing of replacement components, using borkron glass substrates. The replacement process required an extended shutdown (8 weeks) of the neutron guide hall. This work succeeded a 6 week shutdown of the OPAL reactor and the guide hall, during which two new cold neutron guides were installed to accommodate new beam instruments in the neutron guide hall.

4. Beam Validation

All affected guides have since been tested by combination of Au foil activation and time-of-flight methods. Selected examples of the results are shown below.

4.1 Thermal neutron guide fluxes (TG1 & TG3)

The thermal neutron flux distribution measured on TG1 at the second break downstream of the reactor face after remediation is shown in Fig. 2(a) alongside the distribution measured in December 2006 [6] in Fig. 2(b).

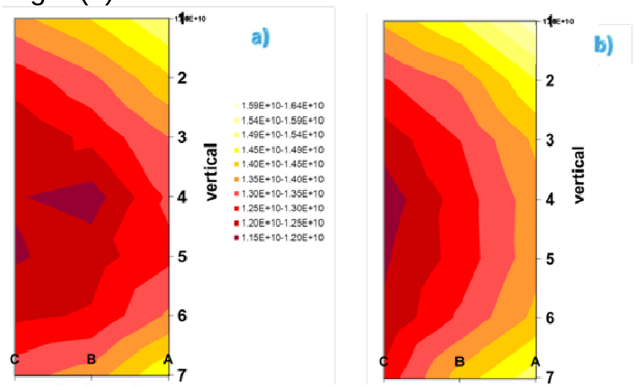

Fig. 2 Flux distribution measured at second break in TG1 guide downstream of the reactor face (~8.6 metres from the source) in a) March 2013, and b) December 2006 (viewed towards the source), with reactor core to right side of image. Contours intervals are 3% of the 2006 measurement.

The spatial flux distribution is essentially the same in both measurements. The vertical component of the distribution shows increased flux at top and bottom of the guide. This is due to reflections from the top and bottom surfaces of the in pile neutron guide. The horizontal component of the distribution shows increased flux at right side of the guide, due to reflections that predominantly occur on the right surface of the in pile neutron guide. The asymmetry in horizontal component has two contributions;

1) the reactor core is to the right side of the image. Hence the thermal neutron flux at the beam tube end is expected to be higher on that side, and
2) TG1 curves from right to left and, although small at this distance, the angular offset favours reflections from the right side of the guide.

The average thermal neutron flux on TG1 in 2013 is 97.5 % of the 2006 measurement [6].
The thermal neutron flux distribution measured on TG1 at the first break downstream of the secondary shutter (at Wombat) after remediation is given in Fig. 3(a), alongside the distribution measured in February 2007 (Fig. 3(b)). The spatial distributions are quite similar.

Average thermal neutron flux measured in 2007 and 2013 are 2.90 x 10^9 and 2.62 x 10^9 n/cm^2/s, respectively, a loss of ~ 10 % beam flux.
Thermal neutron flux measurements on TG3 at the first guide break downstream of the secondary shutter (at Kowari) show that the spatial flux distribution is essentially unchanged. Average thermal neutron fluxes measured in 2007 and 2013 were 2.50 x 10^9 and 2.26 x 10^9 n/cm^2/s, respectively, a loss of ~ 9 % beam flux .

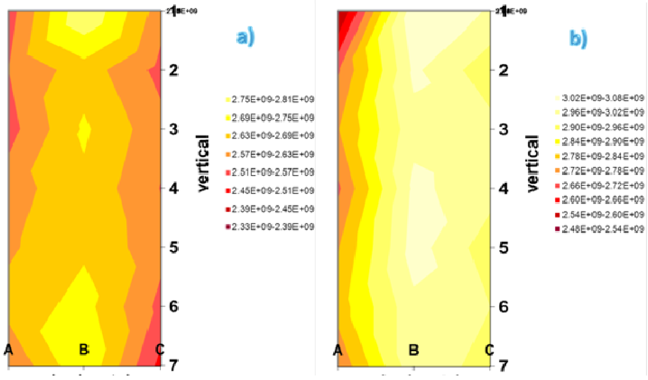

Fig. 3 Flux distribution measured at first break in TG1 guide downstream of the secondary shutter (~ 50 metres from source) in a) August 2013, and b) February 2007 (viewed towards the source). Contour intervals are 2 % of the 2007 measurement.

4.2 Cold neutron guide fluxes (CG1 & CG3)

The average cold neutron flux measured on CG1 at the first break downstream of the primary shutter (~4.6 metres from the cold source) in July 2013 was 96.8 % of the 2007 measurement. The average cold neutron flux measured on CG3 at the second break downstream of the primary shutter (~8.6 metres from the cold source) in 2013 was 107.5 % of the 2007 measurement. Thus it appears that the new in-pile cold guides, which were replaced as part of the installation of two new cold guides, are performing as well as the original guides were soon after reactor commissioning.
The cold neutron flux distribution measured on CG1 at the first break downstream of the secondary shutter after remediation is shown in Fig. 4(a), alongside the distribution measured in December 2006 (in Fig. 4(b)). The average cold neutron flux on CG1 at the first break downstream of the secondary shutter (on Pelican) in 2013 is 106.5 % of the 2006 measurement [6]. The average cold neutron flux on CG3 at the first guide break downstream of the secondary shutter (on Platypus/Emu) in 2013 is 114.2 % of the 2007 measurement [6]. Thus we have measured an overall increase in cold neutron delivery of ~10 %.

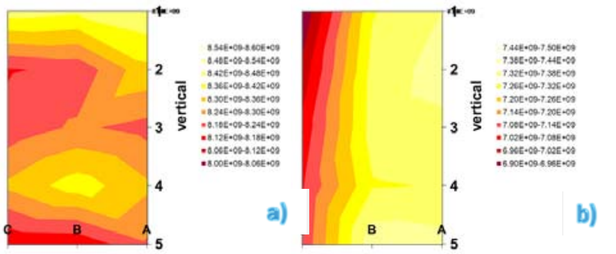

Fig. 4 Flux distributions measured at first break in CG3 guide downstream of the secondary shutter (~ 30 metres from the source) in a) August 2013, and b) June 2007 (viewed towards the source). Contours intervals are 0.8 % of maximum of the 2007 measurement, but the maximum of the 2013 measurement is shifted up by 11.5 %.

4.3 Cold and thermal neutron beam spectra

Preliminary time-of-flight measurements of the neutron spectrum at the first break in the guide after the secondary shutter on TG1 (Wombat) and on CG1 (Pelican) are shown in figure 5. The spectral shapes are quite similar to those obtained at the same locations in 2006-7. The peak wavelengths are λ(TG1) = 1.3 Å and λ(CG1) = 2.2 Å, but in the latter case it is relatively flat until λ = 3.2 Å.

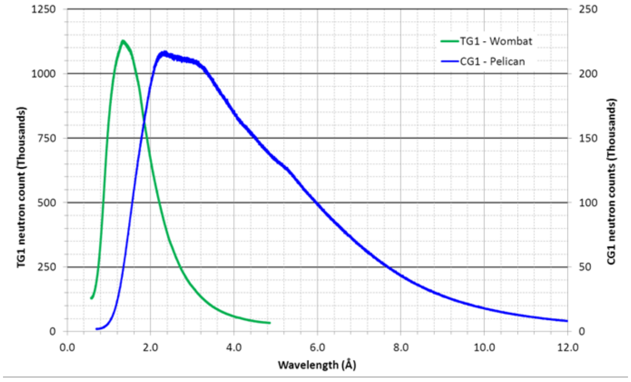

Fig. 5 Preliminary wavelength spectra for TG1 (at Wombat) and CG1 (at Pelican).

4.4 Flux changes at neutron beam instruments

Since remediation, instrument calibration measurements indicate 40% and 90 % flux gains on the Wombat diffractometer (TG1) at λ = 1.54 Å and 2.41 Å respectively [7]. On the Echidna diffractometer (also on TG1) the measured flux gain at λ = 1.60 Å is 55 % (± 10 %) [8]. On the Platypus reflectmeter (CG3) the measured flux gain is ~ 60% over a broad wavelength range [9]. On the Quokka small angle scattering spectrometer (CG1) the flux gain at λ = 5 Å was assessed to be ~50 % [10].

5. Conclusion

This problem would have been avoided if we had been aware at the time of manufacture that the float glass substrates are prone to failure at relatively low non-isotropic neutron fluences, and could have been identified sooner if our planned guide surveillance program had been correctly implemented. Improved guide inspection processes would ensure that future problems are identified at the earliest opportunity. The effect of this delamination on performance of the transport system was severe and well worth the effort and expense of correction.

6. References

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