Analysis of the Causes and Consequences of Neutron Guide Tube Failures

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Neutron guide tubes are used to transport neutron beams from a neutron source to the point of use. These guides are typically rectangular borosilicate glass tubes, coated on the inside with a neutron reflecting coating. Radiation damage can occur both from gamma radiation, and more importantly from thermal neutron capture in the boron in the glass. The guide tubes used at the NIST Center for Neutron Research have internal cross-sections of order 150x60 mm, and extend over lengths as great as 60 m, with gaps for insertion of neutron devices. In this manuscript, the effects of radiation damage and subsequent guide collapse will be presented, along with an analysis of the behavior of the glass fragments.

1. Introduction

The NIST Center for Neutron Research (NCNR) is a user facility for neutron science, providing measurement opportunities for researchers from industry, university, and government. There are seven neutron guides installed at the NCNR to conduct cold neutrons from the source into the guide hall adjacent to the reactor confinement building. The guides consist of rectangular boxes made from borosilicate glass pieces, of inside dimension either 15x6 cm^2 or 12x5 cm^2. The inside surfaces are polished to a very smooth finish, and then coated with ^{58}Ni in most cases, or a series of metal layers called supermirrors. The coatings are typically 10-1000 nm thick. The vertical sides (larger dimension), called plates, are 1.5 cm thick, while the top sections, called rules, are 2.5 cm thick. The guides are made in sections of 1.5 m length (each of which contains several separate pieces epoxied together), that are then aligned into long continuous tubes extending all the way into the guide hall from the face of the reactor. In order to increase the efficiency of transport, the guides are evacuated over their entire length. Inside the confinement building, where the radiation exposure of the guides is highest, they are enclosed in steel casings that are evacuated. The presence of the casing eliminates any stress on the guides from the vacuum required for good neutron transport. In the guide hall, the guides themselves are used as vacuum vessels. At the reactor end, the guide vacuum is terminated by thin metal windows; 1.25 mm thick for NG-1 to NG-5, and 3.2 mm for NG-5, NG-6, and NG-7. In addition, the guide sections inside the biological shield also have windows; 0.79 mm downstream and 1.27 mm upstream for NG-1 to NG-5, and 0.79 mm at both ends for NG-5, NG-6, and NG-7.

In order to place equipment in the neutron beams, it is often necessary to install a "guide cut", or an interruption in the guide, which is usually of the order of several cm in length. At the cut, the ends of the guide are fitted with windows made from aluminum or a magnesium alloy, and the vacuum is generally continued by means of a jumper flex line attached to both guide sections. This jumper is attached at the top of the guide, at the flange shown in Fig.1. Because of this geometry, it is impossible for large pieces of glass to be blown to the other side of a guide cut, and the speed of any gas entering the non-broken guide will be limited by the area of the tube, thus reducing wind velocity by a large factor equal to the ratio of the tube area (1 ½ inch id in worst case) to the guide area (of order 8). As a result, there is no challenge to any system or window on the non-broken side of the guide cut.

On March 23, 2005, the section of neutron guide downstream of the gap for the monochromator at the Fermi chopper spectrometer on NG-6 collapsed (Figure 1). From a reconstruction of the event based on the location of glass at the site of the break, it is probable that the guide broke first on the west side, just downstream of the guide cut, and pieces of the guide then were

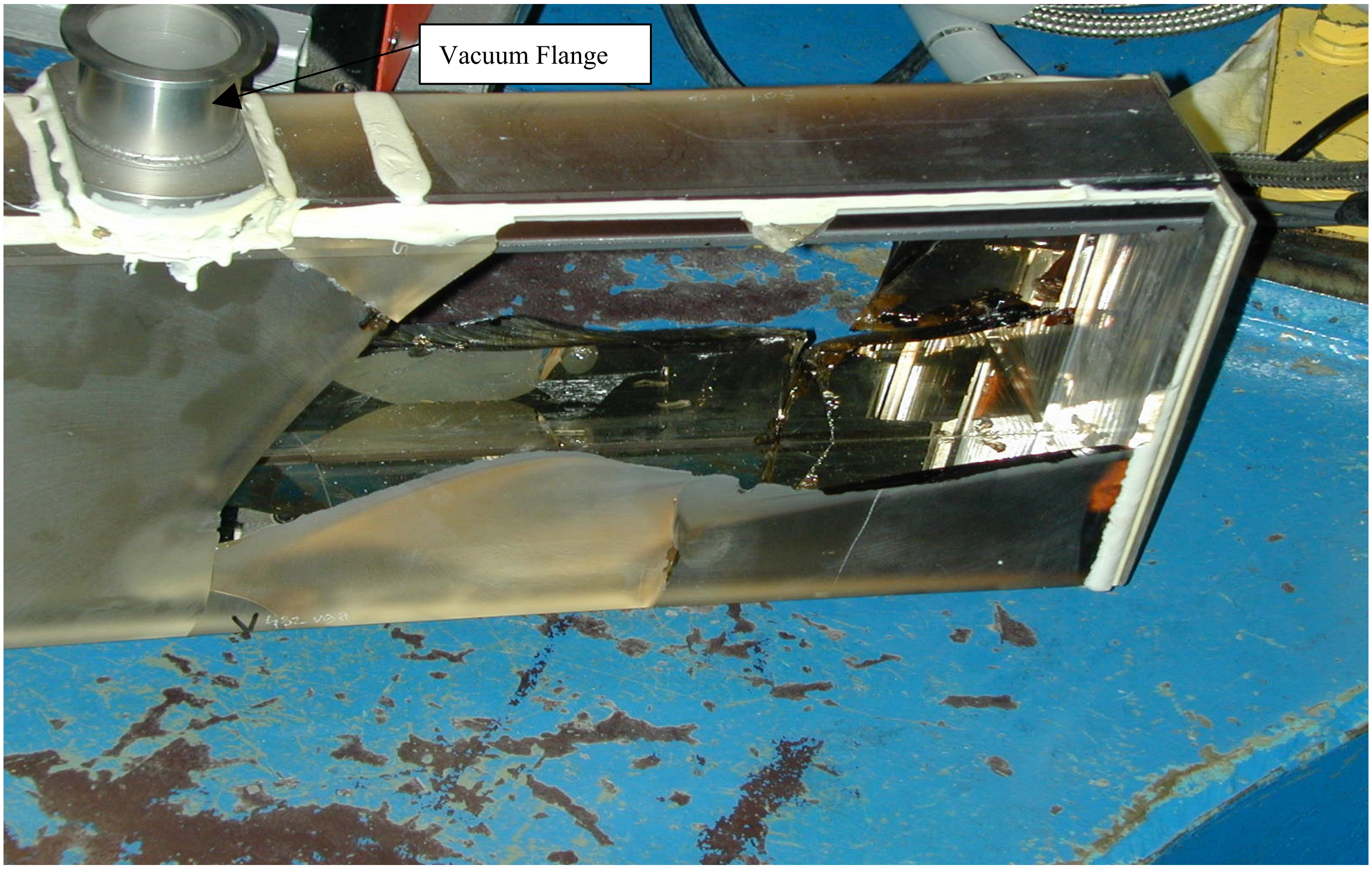

Figure 1. Broken section of guide from NG-6, resting on FCS flight path after removal from remainder of guide. Note that side facing the camera is the west side, which is believed to have broken first. Guide inside dimension is 15 cm high by 6 cm wide, giving scale of photo.

propelled across the width of the guide to break the east side. The amount of guide broken can be seen in Fig. 1. Portions of the glass that broke were carried into the remaining guide section, and propelled 8.48 m down the guide, where they impacted the thin (0.5 mm) window before another monochromator. The results of this impact are shown in Figure 2.

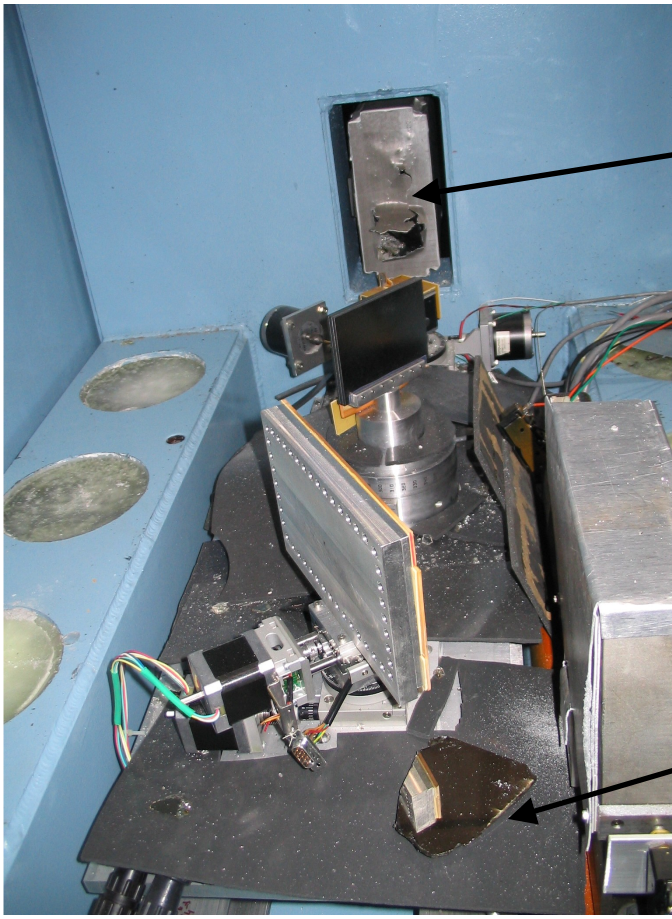

Figure 2. Picture of the other end of the guide, 8.48 m downstream of the break. The thin window is made from Mg alloy AZ31, and was 0.5 mm thick.

This guide tube failure immediately raised several issues, which this memorandum is written to address. The issues are all related to the size of the glass pieces that came down the tube, and to their momentum. In a previous guide break at the beginning of NG-6, the largest pieces that were propelled down the guide were approximately spherical (with rough edges), and approximately 1-2 cm in diameter. Such particles can easily be shown to present no hazard to the cold source and reactor, even if they were to go towards the cold source, which is approximately 40 m upstream. The balance of this memo will address the questions related to the possibility of such failures on an upstream guide in turn.

2. Causes of Guide Failure

It must be noted that there have been approximately 10 similar failures world-wide, and *all have occurred downstream of a guide cut*. The total number of guide tube years accumulated to date is over 350 worldwide. The explanation for the failures has been that the guides are made by plating a metal coating on borosilicate glass, and that at a guide cut, the exposed end of the guide is subjected to the full intensity of the thermal neutron beam. These thermal neutrons are then captured in the boron, leading to emission of an α-particle, which is then stopped in the glass. This creates a large amount of radiation damage, weakening the glass, which then fails under the stress imposed by the vacuum. Questions have been raised recently about radiation damage to the upstream guides as a result of either γ-ray radiation or thermal neutron scattering from the monochromators or other components in the guide cut.

2.1 γ-Ray Radiation Damage

In order to estimate the γ-ray fluence, assume that all neutrons in the guide are captured in Cd, and calculate the fluence rate as follows:

φ = neutron fluence rate in guide $\leq 1.5\text{x}10^9$ n/cm^2/s
Total number of neutrons in guide = φ x area = $1.5\text{x}10^9\text{x}15\text{x}6 = 1.4\text{x}10^{11}$
Each neutron capture creates 9 MeV of γ-rays on average with energies up to 9 MeV; 558 keV is line with highest fraction; assume 500 MeV/cm^2/s =1 mRad/hr (close and conservative)
Then the source strength is $1.4\text{x}10^{11}$ x 9 = $1.3\text{x}10^{12}$ MeV/s

Now, a guide cut is typically 24 cm long, so glass is 12 cm away, and dose rate is

D = $1.3\text{x}10^{12} / 5\text{x}10^5 /4/\pi/12^2 = 1.4\text{x}10^3$ rad/hr = $3.4\text{x}10^4$ rad/day = $9\text{x}10^6$ rad/year (note that we operate only 250 days per year)

This is much less than the dose required for significant radiation effects on the relevant strength-related properties of borosilicate glasses. One measurement[1] found that:
"The effects of ^{60}Co gamma radiation on the strength-related mechanical properties of a borosilicate glass were examined. Although the glass darkened considerably, only a very slight densification was observed after irradiation to levels of 10^8 rads. The strength distributions were not appreciably changed by the irradiation, nor was the calculated slow crack growth parameter (N value). Neither did radiation affect the elastic modulus or the fracture toughness of the glass. Gamma radiation does not affect the strength below 10^8 rads." Other measurements[2] have been performed up to 10^{10} Rads, and have found no dramatic effects the strength-related properties.

2.2 Neutron Damage

For neutron irradiations, it is also possible to estimate fluences and the effects on the properties of the glass. One recent study[3] estimates that each neutron captured by a ^{10}B atom produces 580 atom displacements, which will greatly change the physical properties. CILAS/GMI, the company that constructed our guides, estimates[4] the radiation limit for Borkron glass (which is what we have) as 10^{18} n/cm^2 (based primarily[5] on the initial failures at Saclay), while Borofloat has a limit of 10^{16} n/cm^2. Based upon the experience at NIST, the safe working limit for Borkron should be conservatively set at $< 10^{17}$ n/cm^2.

For a direct illumination of the end of a guide at the downstream end of a guide cut (neutrons that would have been reflected by the portion of the guide removed), based on the performance of the current cold source, the guide will be illuminated by a fluence rate[6] of approximately $1.5\text{x}10^9$ n/cm^2/s, or $1.3\text{x}10^{14}$ n/cm^2/day. Thus, three years of such irradiation would greatly exceed the manufacturer's limit for Borofloat glass, and would approach the conservative limit for Borkron glass. This limit would be approached even more quickly for the proposed deuterium cold source with its greater performance. This is a known effect, and the downstream guide ends at all cuts are covered with neutron absorbing material. In the case of NG-6, the mask was cut from Boraflex, a plastic loaded with boron. This type of mask cannot be cut to close tolerance, so it is likely that some portion of the guide was exposed and directly illuminated, leading to the failure. Since the area was surely small, it took somewhat longer to weaken the guide to the failure point. The remedy is to fabricate masks from boron loaded aluminum sheet, using EDM techniques to eliminate any possible leakage, and this has been done for NG-6 after the repairs were completed.

Another issue that has arisen is whether scattering can cause sufficient damage to cause failure, as this mechanism would affect both the upstream and downstream guides equally. The mechanism proposed is that the scattering causes neutrons to strike the Ni coating at angles higher than the critical angle (which is approximately 0.11 degrees per angstrom). The magnitude of this can be estimated as follows:

The flux in the guide is 1.5×10^9 n/cm^2/s, and if we assume a monochromator that covers the whole guide, then 1.4×10^{11} n/s can potentially be scattered. According to measurements[7] on the pyrolytic graphite crystals used for monochromators, a two inch block has a transmission of approximately 78% for the neutrons in the beam. The monochromators used have thicknesses of order 1-2 mm, and so would scatter approximately .4% of the beam. As before, the first part of the downstream guide is 12 cm from the crystal, so the highest possible scattered fluence rate is

$\Phi_s = 1.4\text{x}11 \text{ x } 0.004/4/\pi/12^2 = 3.1 \times 10^5$ n/cm^2/s or 7×10^{12} n/cm^2 in one year (for isotropic scattering). It would thus require 10^3 years to reach the manufacturer's limit, and isotropic scattering seems not to be a concern.

For small angle scattering, it might be possible to increase this fluence rate by as much as a factor of 20, but this will still be small compared with direct illumination. In addition, it will only affect the guide downstream of a cut, and will pose no threat to the cold source or reactor (see later sections).

From the above, I conclude that it is the direct beam from the guide striking an unprotected area that causes the guide failures that have been observed. This precludes direct failure by this mechanism of any guide section that is directly connected to the reactor or cold source, and eliminates a major concern.

2.3 Other Causes of Guide Failure

The only other possibilities for guide failure that have been identified relate to mechanical issues, such as dropping objects onto the guides, spilling of cryogenic fluids, or failure of a guide at a defect, and human error.

Current operational procedures require that guides must be backfilled with helium before the radiation shielding can be removed. This radiation shielding is massive, and will prevent any objects from hitting the guides. In addition, the radiation levels would prevent removal of the shielding with the reactor operating unless the shutter was closed (the shutters are always closed at reactor shutdown). With the shutter closed, there is no possibility of damage upstream of the shutter location.

Cryogenic fluids are used to cool filters in locations where spillage could result in direct contact between the guide glass and liquid nitrogen, and in fact, one such event has occurred. Although all lines have now been re-routed to prevent a recurrence, it is impossible to guarantee that this cannot happen. However, in the only case that has occurred, the result was a crack and leak, rather than an immediate failure; this is in fact the most probable result. However, it is not possible to guarantee that this is the only mode of failure.

It is possible that a guide could have a manufacturing defect that could result in a sudden, catastrophic failure. Such defects should turn up in the installation and testing phase, when the shutters are closed, and no failures have been reported.

Finally, human error could lead to a problem, such as suddenly opening a valve mounted directly on a steel casing (used to provide vacuum boundaries in high radiation damage areas). This has happened at the ILL in Grenoble, France, and caused a guide failure. The failure is of a quite different type, and is less likely to result in a problem, but is possible. However, all of the casings where this might cause a problem are in the confinement building, and surrounded by massive shielding, which cannot be removed while the reactor is operating. Opening of a valve connected by a long line would markedly slow down the air entry.

2.4 Conclusions

It is highly improbable that a guide will fail catastrophically in a location that allows a direct line-of-sight path to the cold source and reactor. This can only happen through the failure of all operational procedures and administrative controls, along with a second accidental event such as dropping a heavy tool onto an exposed guide. In the next section, the possible consequences of failures will be analyzed, and shown to present no hazard to the reactor.

3. Effects of Guide Failure

Outside of the reactor confinement building, the guides serve a dual purpose – to guide, by total internal reflection, the neutrons to the instruments *and* to provide the boundary for the vacuum required to achieve high efficiency in this transport. The second of these purposes subjects the glass to high stresses, and opens the possibility of damage to other components in the system. The design of the guides is shown in Figure 3, which provides the necessary dimensions for calculation of the stresses. The guide is designed with epoxy attaching the sides (plates) to the top (rules), and a seal of a silicone type adhesive to provide a vacuum tight seal. The most conservative case for the stresses comes by assuming that the epoxy has failed, so that the plates form a simply supported beam of thickness 10 mm and span 150 mm. For this configuration, the maximum bending stress[8] is given by

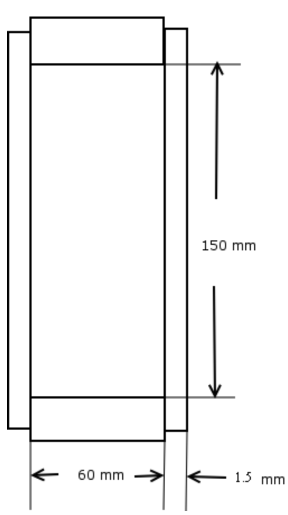

Figure 3. Cross-section of NG6

$\sigma_m = 3/8 \times (L/t)^2 \times P$

where L = span = 150 mm, t = thickness = 15 mm and P = pressure = 10^5 Pa.

This gives a maximum stress of 3.7×10^6 Pa (549 psi), compared to nominal ultimate tensile stresses[9] of greater than 10^8 Pa for a wide range of borosilicate glasses, providing adequate margin in the absence of radiation damage. The best explanation for the glass failures (Section 2) is that neutron capture in the boron in the borosilicate glass used creates radiation damage that lowers the ultimate strength. The mechanism of damage production is that the two charged nuclei emitted, ^{4}He and ^{7}Li, create large numbers of major (non-point) defects (see Ref. 3 which estimates that each capture results in 480 atom displacements). A second possible effect is that the ^{4}He migrates to the pores of the glass, where it will increase the internal pressure as more gas is produced until failure occurs. At any rate, the effect is failure of the glass under the stress imposed by the vacuum.

Although the exact mechanism of guide failures is not known, it is clear from our observations that the failures are sudden and complete, involving the breakage of substantial areas of the plates (see Fig. 1). This presents the possibility of damage to other components from two distinct mechanisms; first, the pressure wave as air rushes into the evacuated volume, and second, the acceleration of glass fragments by the air rushing in.

3.1 Pressure Wave

A sudden ruptures of the diaphragm between two volumes of gas at different pressures is a standard mechanism for generation of shock waves. In the present case, the high pressure is 1.01×10^5 Pa (1 atmosphere, 14.7 psi), while the low pressure is of order 0.1 mm Hg or 13 Pa. Such failures have been extensively studied in the design of instrumentation for synchrotron radiation sources, where long beamlines terminating in a thin metal window are often directly coupled to the ring. Since failure of the window would bring the ring up to atmospheric pressure, with disastrous results for the components in the accelerator, fast-acting valves are used to separate the beamline from the ring. In order to specify the requirements for the valve, it was necessary to experimentally determine the nature of the waves propagating down the tubes, and this has been done for many beamlines. Among the many possibilities, we note particularly a study[10] performed at DESY, a study[11] of mechanisms to delay the pressure wave performed at Münich, a study[12] performed at Berkeley, and a test[13] referenced in all of the preceding papers.

The salient points taken from these papers are:

- A shock wave is formed which propagates down the tubes at supersonic velocity of about 1200 m/s.
- The pressure in the shock wave is small (of order 10^{-6} bars for a starting vacuum of $P < 10^{-8}$ bars)
- Higher pressures are propagated at much lower velocities[14] (285 m/s for approximately 1 bar)

These data are generally consistent with theoretical calculations based upon simple shock waves[14] in polytropic gases (an ideal gas with constant specific heat). Therefore, we can use this theory to estimate the conditions for our case, with a much higher initial pressure (of order 10^4 bars).

The shock strength $z = (P_s - P_v)/P_v$, where subscripts s,v indicate the shock and the initial vacuum, can be shown to be given by the transcendental equation:

$$\frac{z}{\gamma(1+\frac{\gamma+1}{2\gamma}z)} = \frac{2}{\gamma-1}\left\{1-\left[\frac{P_0}{P_v}(1+z)\right]^{\frac{(\gamma-1)}{2\gamma}}\right\}$$

Where $\gamma = 1.4$ = ratio of specific heats of air

This equation can readily be solved to yield z = 39.5. This value can be used to derive the pressure in the shock = 526 Pa (4 mTorr); the Mach number = 6.1; the speed of the shock = 945 m/s; and the density of the air in the shock = 0.001 kg/m^3 (normal air has density 1.5 kg/m^3). Thus, the shock wave is of low energy, and presents no threat to any component (the peak reflected shock pressure[14] would be < 3000 Pa, so the sign of the pressure on any window would not change).

3.2 Simple Estimate of Fragment Acceleration

For this simplest estimate, the velocity of the air entering the guide will be that measured in Ref. 13, U = 285 m/s. The length of guide to be considered[6] is L = 54 m, the longest direct line of sight, which is the distance from the guide cut in NG-6 to the inner end of the guides (excluding in-pile parts, which are separated from the other guides by an air gap and two windows).

It is conservative to assume that the air speed is constant at 285 m/s, so we can estimate the speed of any projectile as follows:

$V_p = ½ \times C_D \times \rho_{air} \times U^2 \times \Delta t \times A_p / (\rho_p \times vol)$
Where
V_p = velocity of projectile (piece of glass) in m/s
C_D = coefficient of drag = 1.98 for a slab (see Table 1 below)
ρ_{air} = density of air =1.2 kg/m^3
U = velocity of air = 285 m/s
L = length of evacuated guide = 54 m
Δt = L/U = 0.19 s
A_p = frontal area of projectile
vol = volume of glass piece
ρ_p = density of projectile = 2.51x10^3 kg/m^3 for Borkron 7 (our guide glass)
Thus,
$V_p = 1.4\times10^4 \times A_p / (\rho_p \times vol)$

Shape and Orientation	C_D
Large Right Cylinder, side on	1.2
Sphere	0.47
Rod, End on	0.82
Disk or square slab, face-on	1.17
Cube, face-on	1.05
Cube, edge-on	0.80
Long rectangular member, long narrow face-on	2.05
Long rectangular member, edge-on	1.55
Narrow strip, face-on	1.98

Table 1. Representative drag coefficients[15]

In Ref.15, it is shown that the velocity of a projectile for which there is a 50 % probability of penetrating a thin metal target, V_{50}, can be correlated as a linear relationship between two dimensionless variables. These are the dimensionless thickness h/r, where h = plate thickness and r = radius of equivalent sphere (sphere with same mass), and the dimensionless velocity $V_{50} \times \rho_p / (\sigma_t \rho_t)^{1/2}$,

where
ρ_t = density of target = $2.7x10^3$ for 6061 T6 Aluminum,
σ_t = yield stress of target material = $2.4x10^8$ Pa for Aluminum 6061 T6.
From the lower bound of the given correlation (Fig. 6-14, reference 15), and the values given for the parameters above, a conservative expression for V_{50} can be written as:

$V_{50} = 1.9x10^6 \times (h/r)/ \rho_p$

Then a necessary condition for containment of all projectiles is $V_{50} / V_p > 1$.

$$\frac{V_{50}}{V_p} = \frac{1.9x10^6 (h/r)/\rho_p}{1.44x10^4 A_p / \rho_p / vol}$$

Or

$$\frac{V_{50}}{V_p} = 1.3x10^2 \times vol/A_p \times h/r$$

But, vol/A_p is a characteristic dimension of the projectile, and by comparison for a sphere, it is 4r/3, so that

$$\frac{V_{50}}{V_p} = 173 \times h$$

Thus, the interesting result is that the margin for penetration is independent of the size, shape or mass of the projectile (only in this very special case). The origin of this effect is easy to see, as the momentum change is independent of mass, and linearly dependent on frontal area, so that the velocity is proportional to area over volume, while the penetration probability is just proportional to 1/r, which is again area over volume.

The above relation is overly conservative, as the fragment acceleration is of short duration, while the free (ballistic) flight is long, and during the ballistic portion, the velocity will be reduced by drag. To illustrate, it is necessary to choose a fragment size and frontal area, in order to estimate the drag effect. Assume that the fragment is of dimension 11x14x1.5 cm^3, with the 14x1 fragment facing the wind (11 cm dimension oriented along guide axis).

Then $V_p = 1.44\text{x}10^4 / 0.11/2.51\text{e}3 = 52$ m/s, and the distance traveled during acceleration is D = 6 m, so that the ballistic flight distance = 48 m. This leads to an equation that can be easily solved.

$\frac{dV}{\partial t} = -1/2\rho_{air} C_D V^2 / m$, where m = mass of fragment.

Set a $= 1/2\rho_{air} C_D A_p$ /m = $1.33\text{x}10^{-3}$/m, or

a = $\frac{1/2\rho_{air} C_D A_p}{\rho_p A_p \ell}$ = $3.8\text{x}10^{-4}/\ell$, where ℓ = length of fragment along the guide axis

$$\frac{dV}{V^2} = -adt$$

1/V = at+b, and since $V=V_o$ at t=0, then $1/V=at+1/V_o$, from which

$V = \frac{1}{at + \frac{1}{V_0}} = \frac{dx}{dt}$, where x = distance along the guide in ballistic flight

Thus

$dx = \frac{dt}{at + \frac{1}{V_0}}$, and

$x = \frac{1}{a}\left\{ \ln\left(\frac{at + 1/V_0}{1/V_0}\right) \right\}$, after substituting x = 0 at t = 0

Rearranging terms,

$$t = \frac{1}{V_0 a}\left\{ e^{ax} - 1 \right\}$$

Substituting this into the earlier expression for V, and rearranging terms,

$V = V_0 e^{-ax}$ is the expression for V anywhere down the guide. For the assumed projectile, $11x14x1.5cm^3$, the mass m = .580 kg, or ℓ =11 cm, and a = $3.5x10^{-3}$ and e^{-aL} = 0.85. Thus, the velocity will be decreased by 15 % by the drag during the ballistic flight. Thus, for this fragment, which was the biggest one found in the NG-6 collapse,

$$\frac{V_{50}}{V_p} = 173h/.85 = 204h, \text{ with h in meters}$$

This would provide a safety factor of 1.29 for such a projectile, *even if the only barrier were the ¼ inch (6.35 mm) thick cold source vessel*. Since this is less than might be desirable, the sources of over-conservatism must be considered.

3.3 Refined Estimate of Fragment Acceleration

The most conservative assumption in the analysis of section 3.2 is that the velocity of the air entering the guide tube, and thus accelerating the glass pieces, is constant at 285 m/s until the guide is full, after which all air motion stops. This neglects the effects of friction, which leads to sonic choking, and reflection of the flowing air, which would create a backflow after the guide has been filled with a column of rapidly moving air. The first of these may be treated reasonably well by considering the flow of air as a compressible ideal gas; treatment of the second is more complex, and will be omitted for this estimate, leaving it still quite conservative.

The starting point for a refined estimate is the theory of the flow of compressible gases in long tubes, as discussed[16] in many standard courses and texts. The salient result from this theory is that, irrespective of the initial velocity, whether sub or super sonic, friction in a long tube will drive the flow at the tube end to the velocity of sound. Thus, supersonic flows will be slowed, while subsonic flow will accelerate (with concomitant changes is density, pressure and temperature) in ways which can be calculated for isentropic flow (adiabatic, ideal gas). The latter case leads to the well known phenomenon of sonic choking. To use this result, it is necessary to discuss several factors.

First, the nature of air flow into the tube (after the shock wave has passed) must be addressed as a 'simple wave", proceeding down the tube. In view of the nature of the flow, with one atmosphere behind the wave face and very low pressure ahead of the wave front, the leading edge will always move at or very close to the velocity of sound (only a shock wave can exceed this velocity). This fact can be used to derive the velocity of the air at the beginning of the tube as a function of the length of tube traversed and the friction loss.

Second, the friction factor of the guide tubes, which depends on the roughness (for guide glass this is so small that it can be neglected) and the Reynolds number of the flow, must be estimated. This in turn requires knowledge of the mass flow rate, which depends on the friction loss, so the exact solution is iterative. However it is conservative to simply use the mass flow that would exist at the beginning, when all of the air is moving at the velocity of sound. Later in the flow, when mass flow drops, the Reynolds number will decrease, and the friction factor will increase, so that using the initial condition will underestimate the friction losses, and hence over-estimate the air velocity accelerating the glass.

Finally, it is necessary to calculate the air velocity and density at the exact location of the fragment, and thus to integrate over the time of the flow. However, the density of the fragments is large when compared to air, so that correction is actually small if one assumes that the relevant conditions are those at the entrance (site of break) of the guide. The acceleration of a fragment at that point is shown as a function of time after break in Fig. 4, which clearly shows the conservatism of the previous section.

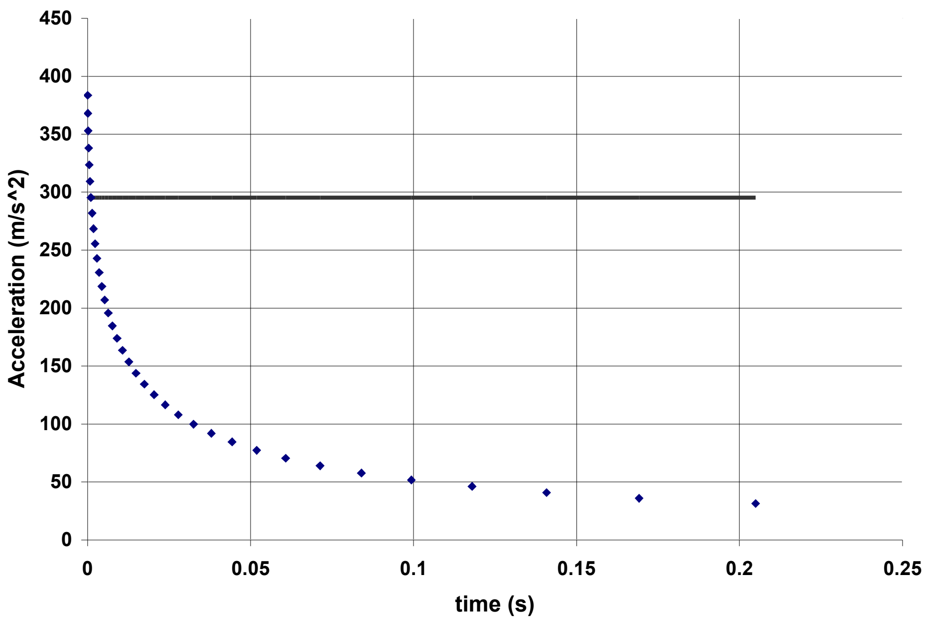

Figure 4. Acceleration on glass fragment at opening; solid line is assumption of section 3.2

Using these results, it is then possible to estimate the speed of a fragment accelerated by the inrushing air, and use that value in the ratios discussed in the previous section. For completeness, the relevant formulae are reproduced here.

$$\frac{4f}{D_h} = \frac{1-M^2}{\gamma M^2} + \frac{\gamma+1}{2\gamma}\ln\left(\frac{\frac{\gamma+1}{2}M^2}{1+\frac{\gamma-1}{2}M}\right)$$

$$\frac{p}{p_*} = \left(\frac{1}{M}\frac{\frac{\gamma+1}{2}}{1+\frac{\gamma-1}{2}M^2}\right)^{1/2}$$

$$\frac{T}{T_*} = \frac{\frac{\gamma+1}{2}}{1+\frac{(\gamma-1)}{2}M^2}$$

Where

f = Friction factor, a factor of Reynolds number and roughness
L = length of tube to reach speed of sound
D_h = Hydraulic diameter = 4*r_h, r_h = flow area over perimeter
M = Mach number = actual velocity/velocity of sound = $(\gamma p/\rho)^{1/2} = (\gamma RT)^{1/2}$
R = gas constant = 268 joules/K/kg for air
γ = ratio of specific heats (C_p/C_v) = 1.4 for air
p = pressure (Pa)
T = Temperature (K)
$_*$ indicates quantities evaluated when M=1 condition is reached in tube

In order to use these results, it is necessary to estimate the friction factor f, and use that to calculate the length L to reach M=1, knowing that at the entry we have air at atmospheric conditions. To do this we must estimate a Reynolds number; noting that f decreases as the Reynolds number increases, it is conservative to use the initial value just after the guide breaks, when atmospheric air is moving at M=1. This gives a Reynolds number of 2×10^6, which in turn gives f=0.0025, and this will be the smallest value achieved. The conservatism in this estimate could be removed by calculating an average f after choosing the one given, and iterating, but it is not a large effect. This allows derivation of results shown in Figure 4, which can be used to derive a maximum velocity for the fragment considered above of 13.3 m/s, compared to the value given for the simple assumption of 58 m/s, a reduction of a factor 4.3. This changes our penetration criterion to

$\frac{V_{50}}{V_p}$ = 890h, where h is the window thickness in meters

This implies that a window of thickness 1.5 mm has a 50% chance of being penetrated, and thus gives a factor of safety of nearly 6 for penetration of the cold source itself.

As a test of this procedure, the fragment that went through the window in NG6 has also been calculated, and inserted into the framework developed. This gives a value for the ratio
$\frac{V_{50}}{V_p}$ = 2690h for Al6061,
which in turn implies that for the 0.41 mm window, made of Mg alloy AZ31, which has a lower tensile strength than Al6061-T6,

$$\frac{V_{50}}{V_p} = 1808*.00041 = 0.74$$

This confirms that the revised method is not seriously underestimating the velocity of glass fragments in this case. From this, the margin of safety of nearly 6 found above is likely conservative.

3.4 Effects of Additional Windows

However, on the guides with the thinnest windows (NG1-NG4), there are three windows: the inner end of the casings, just outside the in-pile section, 1.27 mm; and the downstream and upstream windows on the in-pile section, 0.79 and 1.27 mm respectively. These windows would slow down the projectile before it could get to the cold source, providing ample margin against damage to the cold source. However, one cannot simply add thicknesses – separated plates do not present as much stopping power as a monolithic plate of the same thickness. An example for plates of 2024-O aluminum alloys[17] is given in Table 2. Other penetration data are given[18] in reference 16, and other references therein.

Target		Ballistic Limit $\cong V_{50}$ (m/s)	
Material	Thickness (mm)	Blunt-nosed	Conical Nose
Aluminum 2024-O	1.66	61.9	52.8
	3.2	93.0	95.2
	4.8	135	144
	6.4	142.4	184.4

Table 1. Data from Ref. 15 on penetration of blunt, 35 g and conical head, 29 g projectiles of diameter 12.57 mm and length 38.1 mm.

From the table, each additional layer of equal thickness increases V_{50} by only 1.5, rather than the factor of 2 that would be expected naively. In fact the data suggest that thicknesses should add root-mean-square. Using this method for NG1-4, the effective thickness is 6.5 mm, giving additional margin for the cold source vessel. For NG5-7, the window thicknesses are 3.175, .79 and .79, giving an effective thickness of 7.1 mm. Inserting these values into the equation for V_{50}/V, the margin will increase. In some cases, the fragment will be completely stopped by the upstream window (e.g. for NG5-7, the ratio $V_{50}/V = 2.8$, and even for NG1-4, the ratio would be 1.13).

4.0 Summary and Conclusions

- All observed guide failures world-wide (approximately 10) have occurred *downstream* of a guide cut.
- There is no line-of-sight path from the location of the break to the cold source and reactor. The only path is restricted to chunks less than 2 cm in diameter. (Note that spherical chunks are *much* less dangerous because C_D is approximately 1/3 of slabs).
- The cold source jacket alone provides adequate protection against a projectile larger than any observed; the windows on the guides provide additional margin.

- NCNR Operational procedures require that guides be backfilled with helium or nitrogen prior to being exposed to possible damage by falling objects. If the reactor is operating, the shutter would be closed, providing complete isolation of the break.
- In the only incident involving cryogenic liquids, the guides cracked and leaked, but did not fail catastrophically.
- If all controls failed, and a guide was broken in a place where debris could go directly upstream to the reactor end of the guide, there could be significant (depending on fragment shape) damage to the in-pile guides.

However, based upon the probable destruction of the in-pile guides if such a failure were to occur, a decision to use thicker windows (at least1/8 inch) should be considered. It is very difficult to calculate probabilities of such a failure; there have only been 10 worldwide during approximately 300 guide years, and all have been downstream of a guide cut. This alone can be used to derive a failure probability of less than 8 % per year for the 7 NIST guides. Adding in the knowledge of the failure mechanisms, and that administrative controls, would reduce that to less than 0.1 %/year.

This paper provides the basis for decisions concerning upstream windows in neutron guides subjected to high stress as a result of vacyym.

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