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Feature Article

Failure analysis of a 41-m long neutron beam line guide

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Abstract

A 41-m long glass tube structure, used to guide low energy neutrons to a backscattering spectrometer, fractured in five places in mid-September 2011. The structure was made of hundreds of 1.5 cm or 2.5 cm thick bonded borosilicate glass plates. Fractographic examination identified the fracture origins and the stress states when fracture occurred. The cause of fracture was traced to damage introduced during the magnitude 5.8 earthquake that occurred 150 km away in Virginia on August 23, 2011. Lateral displacements of the earth created bending and torsional displacements in the beam line of as much as 2 mm caused cracks to form in the glass plates. Finite element modeling verified the displacements and stresses that caused damage.

Keywords: Failure analysis; Fractography; Borosilicate glass; Earthquake; Neutron beam line

1. Introduction

Neutron guide 2 (NG-2) at the NIST Center for Neutron Research (NCNR) broke while being evacuated on 19 September 2011 in preparation for experimental use. The reactor itself was off line for a major research facility upgrade. Fig. 1 shows NG-2, one of seven neutron guides used to carry cold neutrons from a liquid hydrogen source in the NIST reactor into an experimental hall that contains neutron instrumentation.[1,2] The instruments are used to perform experiments in chemistry, materials science, physics, and biology. The guides extend over lengths as great as 60 m, with gaps for insertion of the instruments used to evaluate materials. NG-2 was 41 m in length and was made of hundreds of precision ground and polished glass plates that were bonded by epoxy. NG-2 is used with a backscattering spectrometer described in Ref. 2.

A few weeks earlier on August 23rd, a powerful magnitude 5.8 earthquake occurred in the Washington region causing modest damage to building and structures throughout the region. The authors of this article were all at NIST and can attest to the significant disturbance that went on for almost a minute. All of the buildings at NIST were evacuated and fortunately, there were no injuries or fatalities. The epicenter was under the small community of Mineral over 150 km away in north central Virginia. The NCNR beam lines were all examined for evidence of damage and none was detected. A vacuum check was also conducted and confirmed there were no leaks. Guide NG-2 was filled with helium after the vacuum check test and then again evacuated after three more weeks. During the second evacuation, a major failure of the guide occurred with fractures at several locations.

What caused the fractures in NG2? Did the earthquake cause damage that was only revealed later? Were there problem with the glass or its installation? Did normal operational use create the cracking? Was there radiation damage to the glass? Did stresses from the external pressure loading (when the interior was evacuated) cause cracking? Did the contact points that supported the glass cause cracking? Was debonding of the glass from the epoxy a problem? Was there accumulated damage over a decade or more? These were the questions that we faced at the beginning of the investigation. This article is meant not only to document an unusual case study, but also to demonstrate some of the key approaches to conducting a large failure analysis and what can be accomplished with rudimentary fractographic analysis tools.[3]

A companion manuscript[4] emphasized the numerical analysis and finite element modeling, a key part of the failure analysis. The present manuscript focusses on the fractographic analysis. Together, the finite element and fractographic analyses provided a definitive interpretation of the cause of fracture.

2. Materials and methods

The tubular guides shown in Figs. 2 and 3 consist of repeated sections of 1.5 m long rectangular boxes, each made from multiple borosilicate glass slabs[5,6] that are bonded together by a

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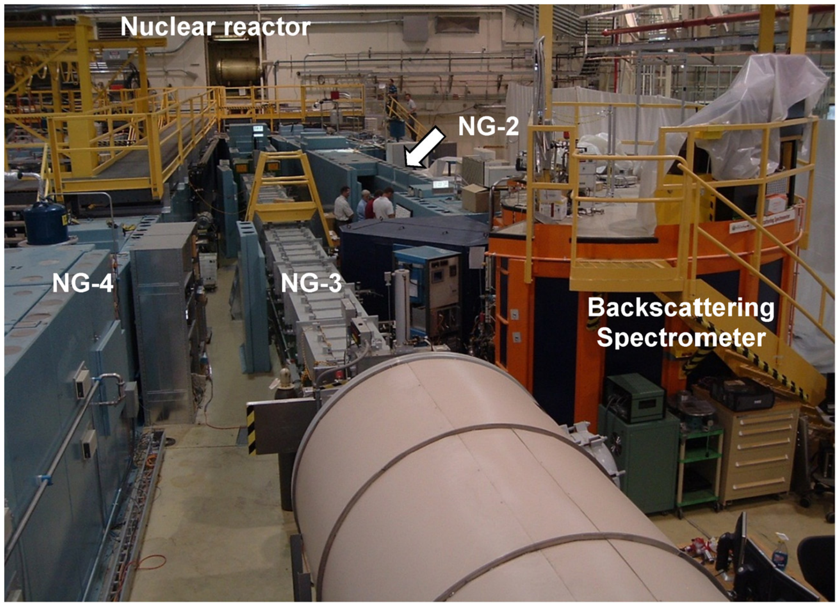

Fig. 1. The instrument hall with neutron beam lines. The source reactor is behind the wall at the far end of the hall. The fracture occurred in beam line NG-2 at the location marked by the large arrow where several of the authors are standing. This beam line is used with the backscattering spectrometer.

strong epoxy. The glass is a specialty borosilicate crown grade containing 12% mass fraction boron.[5,6] This is more than some borosilicate glasses and is beneficial since the boron absorbs neutrons that are not reflected in the guide tube. The elastic modulus is listed as 70 GPa; Poisson's ratio, 0.214; and the thermal expansion (from 20 °C to 300 °C) was 5.2×10^{-6} K^{-1}.[6] Values of strength or fracture toughness were not reported.

The guide tubes have inside dimensions of either 15 cm × 6 cm or 12 cm x 5 cm. The inside surfaces are polished to extraordinary smoothness and flatness, and then coated with ^{58}Ni in most cases, or a series of metals called supermirrors. The coatings are typically 10–1000 nm thick. The vertical glass side pieces, called "plates," are 1.5 cm thick, while the top and bottom pieces, called "rules" are 2.5 cm thick. The guides are made

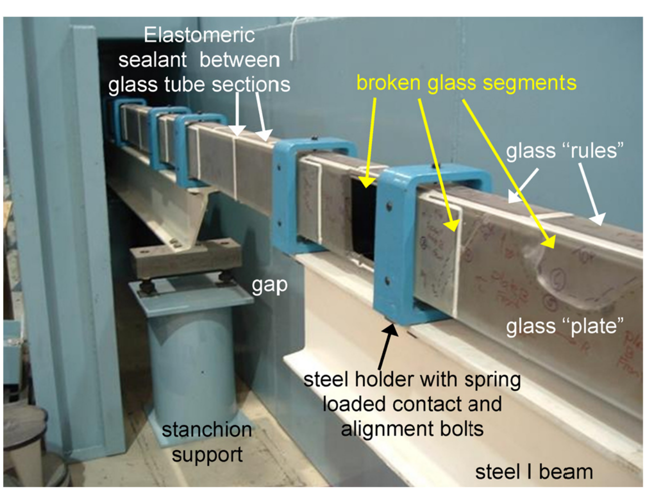

Fig. 2. The broken guide. One glass plate fell out and landed on the floor. Cracks occurred in several locations along the beam guide. None of the fractures started at the contact points. This view is looking toward the reactor. Large shields around the beam line were removed to gain access.

in sections of 1.5 m length, that are then aligned into long continuous tubes extending all the way into the guide hall from the face of the source reactor. The epoxy-bonded neighboring 1.5 m long sections are joined only by a white elastomeric sealant at their ends.[1,2] Since air or any other gas scatters useful neutrons out of the beam, the guides are evacuated over their entire length when in use. When not evacuated, they are back-filled with helium gas.

The glass guides are supported by multiple steel I-beam sections to which they are connected by open rectangular-shaped steel holders. Each holder contains set screws and spring-loaded plungers that touch the glass at six points (two on each side, one each on the top and bottom). The screws and plungers have rounded tips and the screws on one side are spring loaded. The steel holders are bolted to the I-beams, which sit on large round stanchions that are supported by "isolation pads" which rest on concrete pilings. Under normal usage conditions when the tubes are evacuated, the only mechanical loadings on the glass tubes are from the external atmospheric pressure and from the effects of gravity. The epoxy bond between the glass pieces in a tube segment and the elastomeric bond between tube segments prevent direct glass-to-glass contact.

Figs. 2 and 3 show the fractures in the structure. The broken pieces could not be removed from the instrumentation hall after disassembly, since NIST policy is that pieces with even trace levels radiation cannot be removed without stringent controls. Therefore, nearly all the fractographic examinations were done with the unaided eye or with the jeweler's 7 power loupe in the

[1] Tecsil AC 452, Den Braven sealants, Oosterhout, Holand.

[2] Commercial products and equipment are identified only to specify adequately experimental procedures and does not imply endorsement by the authors, institutions or organizations supporting this work, nor does it imply that they are necessarily the best for the purpose.