Nuclear Instruments and Methods in Physics Research A276 (1989) 496-499
North-Holland, Amsterdam

LIGHT-PIPE OPTICAL JOINTS MADE FROM SILICONE DISKS

L.K. RANGAN * and E.I. SHIBATA

Purdue University, W. Lafayette, IN 47907, USA

J.S. LOOS **

Argonne National Laboratory, Argonne, IL 60439, USA

Received 7 November 1988

A method of fabricating optical joints from a transparent silicone rubber compound is described. In an experiment lasting five years the disks were used successfully to join acrylic light pipes in a photomultiplier detector system. They proved to be highly reliable, resistant to aging and radiation damage, mechanically flexible, easy to make and convenient to use.

1. Introduction

Reliable optical joints are crucial in detector systems which use photomultipliers to sense faint light signals. Among the desirable properties are optical transparency, thermal and mechanical stability, resistance to aging and immunity to radiation damage. The issue of reliability is especially important for large systems having hundreds or thousands of optical joints, many (or all) of which may be virtually inaccessible for repair after the entire facility has been assembled and placed into operation.

This note reports the successful use of optical joints made from flexible, transparent disks of silicone rubber. These optical joints were used over a five-year period in the barrel calorimeter system [1] of the High Resolution Spectrometer (HRS) [2] at the PEP e^+e^- storage ring operated by the Stanford Linear Accelerator Center. The method of fabrication and installation of the optical joints, as well as their optical and aging characteristics, are discussed.

2. Experimental arrangement and light pipe joint requirements

The arrangement of light pipes and optical joints used in the experiment is shown in fig. 1. There were 160 photomultipliers in the system, and 3 optical joints per photomultiplier. The assembly sequence of the spectrometer dictated that joints be placed at both ends of long acrylic light pipes. The light pipes, which had diameters of 5 cm and lengths of 135 cm, passed through drilled holes in the thick (117 cm) steel yoke of the spectrometer magnet. The calorimeter modules and the photomultiplier housings were both mounted to the magnet steel.

The optical integrity of the joints had to be maintained in spite of thermal expansion mismatches between the acrylic light pipes, the magnet steel, and the aluminum brackets used to mount the photomultiplier housings to the magnet steel. In addition, there were troublesome magnetic motions associated with the magnet pole pieces, which were assembled by bolting together 12 large steel blocks. Whenever the spectrometer magnet was charged to its full current, the magnetic forces on the steel stretched the bolts such that longitudinal motions of the order of 0.5 mm were observed at the light pipes. Thus, in addition to the other requirements, the joints were required to be springy and flexible in order to maintain optical continuity between the sections of acrylic light pipes.

The optical joints located in the interior of the spectrometer could not be replaced without a major disassembly of the facility. Therefore, it was imperative that these joints be designed to retain all of the desired properties for the lifetime of the HRS experiment.

The optical joints were cast prior to installation in the form of disks of 5 cm diameter and 3–6 mm thickness. Light pipes were connected by inserting a disk between the ends of the pipes, wrapping the joint with aluminum foil, and covering it with a thin black rubber tube to seal against light leaks. It was also

* Now at Lockheed Space and Missiles Co., Sunnyvale, CA 94086, USA.

** Now at AT&T Bell Laboratories, Murray Hill, NJ 07974, USA.

0168-9002/89/$03.50 © Elsevier Science Publishers B.V.
(North-Holland Physics Publishing Division)

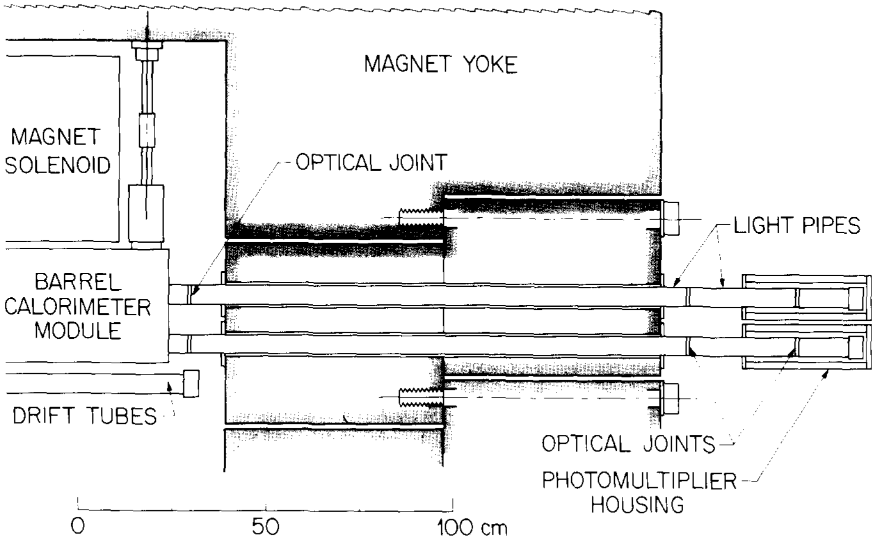

Fig. 1. Layout of the light pipes and optical joints. Joints were located on both ends of a light pipe which penetrated through the steel pole pieces of the magnet. The joints located inside the magnet volume could not be accessed after the spectrometer was completely assembled.

convenient to use silicone disks for the optical union between the photomultiplier and its light pipe in order to simplify repair and replacement operations on the photomultiplier or base. As a final step, a slight longitudinal compression was applied to the entire light-pipe column to squeeze out any air bubbles trapped between the silicone and acrylic.

3. Fabrication of the optical disks

The disks were made from a silicone rubber compound, having the trade name RTV615, manufactured by General Electric Co. This compound is supplied in a two-component kit, part A and part B (curing agent). For use as a potting compound the manufacturer recommends a thermal cure of a mixture of 10 parts A to 1 part B. However, this curing procedure produced a silicon rubber that was much too firm and inflexible for our needs. Experimentation with the mixture ratio, the curing conditions and the fabrication techniques eventually led to the following procedures for preparing the optical joints:

(1) The mixture proportions are 35 parts A to 1 part B, by weight. The two components are measured into a clean beaker and thoroughly mixed at room temperature.

(2) The mixture is then placed under a bell jar and the trapped air is pumped out. The mixture froths during the pump-out, so a large beaker is recommended. After pumping, air may be let back into the bell jar to suppress the froth. When the mixture is free of air bubbles, it has a thick-syrup consistency and is ready to be cured. If desired, the curing step may be postponed, as the mixture will remain usable for at least two days if it is kept under ordinary refrigeration.

(3) The liquid mixture is then transferred to a suitable forming mold to be cured. A convenient way to transfer a measured volume of the liquid is to use a disposable hypodermic syringe without its needle. The curing should be done in a clean oven with adequate temperature control. The optimum curing for the required flexibility and softness is at 50–55 °C for a time of 12–14 hours. The sponginess of the final product is affected more by the temperature than by the length of time.

(4) For the HRS experiment simple molds for 5 cm diameter disks were machined (and polished) from acrylic sheet of the desired thickness (in the range from 3 to 6 mm). The molds are clamped down in batches to a 1.25 cm thick acrylic base sheet for the curing operation. The removal of the cured disks is facilitated by using a 50 μm thick Mylar gasket between the mold and the base sheet.

(5) After the cured disks have cooled to room temperature, they are carefully peeled from their molds, such that they remain on the Mylar gasket. If the disks are to be stored, a second Mylar sheet is placed on the open face of the disk to prevent accumulation of dust. The disks can be stored indefinitely at room temperature or under ordinary refrigeration. Since the disks are somewhat sticky, the Mylar sheets also provide a con-

venient means of handling them when they are being installed. The Mylar is easily peeled away from the disk at the time of installation.

These procedures produce silicone disks which are optically clear, mechanically flexible and spongy, and which wet well to polished acrylic or glass. The disks do not appear to undergo significant additional curing at room temperatures. These disks do not support substantial transverse mechanical loads, however, so the surfaces to which they are attached must be independently supported. The disks should be slightly compressed longitudinally in order to squeeze out any air bubbles trapped between the surfaces.

The RTV615 compound can also be used for applications not requiring significant mechanical flexibility. The stiffness of the material depends on the ratio of the parts A and B, as well as on the curing temperature and time.

4. Optical properties

The index of refraction (in white light) of the silicone was measured by focussing on a flat object placed on a microscope stage before and after covering the object with a sample disk. If a disk of thickness t shifts the focal plane by a distance Δt, then the index of refraction is given by

$$n = \frac{t}{t - \Delta t}.$$

The index of refraction of the silicone was determined by this technique to be $n_1 = 1.46 \pm 0.03$. The refractive index of the acrylic used in the light pipes was measured in identical fashion, and found to be $n_2 = 1.48 \pm 0.01$.

The reflection coefficient at normal incidence is

$$r = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2,$$

indicating that the reflection loss at the joint is negligible. This result was confirmed by photometer measurements of transmission at wavelengths of 433 and 500 mm through sections of acrylic pipes with and without an additional 3 mm silicone disk placed in series; this check showed reflection losses less than 1–2%. Losses at this level were insignificant compared to light absorption in the long acrylic pipes, which had 1/e attenuation lengths of 2–3 m at a wavelength of 420 nm.

5. Observed long-term reliability of the optical joints

The light pipes, joints, and photomultiplier assemblies were installed in the HRS facility in the spring of 1981. The HRS was first exposed to $e^+ e^-$ colliding beams in the fall of 1981, and the facility was operated thereafter for 6–9 months per year until it was decommissioned in the spring of 1986. Aging of the calorimeter potentially could arise in any of its components: scintillator, light collectors, light pipes, light joints, photomultipliers, bases, or analog-to-digital electronics. Aging effects on the entire system, including the light collection system, were indirectly monitored throughout the life of HRS operations by examining the pulses from Bhabha electrons (when $e^+ e^-$ beams were available) or cosmic rays (when $e^+ e^-$ beams were not available). In actual performance, the calorimeter showed little aging in any of its parts.

During the five-year period of HRS operation, none of the optical joints located inside the magnet volume could be accessed, and there was no need to do so since none showed evidence of significant deterioration. There were, however, many opportunities to examine silicone disks which had been installed outside of the magnet yoke because approximately 1% of the photomultipliers and 7% of the bases failed, and were replaced, annually. In addition, during each major annual shutdown, typically 10–20% of the photomultiplier assemblies were removed to allow access to or installation of other subsystems of the HRS. In all, ~ 200 of these joints were replaced over the five years, and another ~ 50 joints were opened for visual examination. None showed significant loss of transparency or obvious signs of deterioration, such as cracking, disintegration, or development of bubbles or voids.

A recurring problem was created by the noticeable movements of the magnet pole pieces whenever the HRS magnet was ramped up or down. These motions would typically cause a few (1–3%) of the light pipe joints to develop an air bubble between the silicone and acrylic surfaces. The existence of such air bubbles could be inferred from reduced average pulse amplitudes of Bhabha electrons and/or cosmic rays. Such bubbles could be squeezed out by applying an additional longitudinal compression to an affected light pipe column, and this became a common procedure. Often, this procedure also was carried out when a photomultiplier or base was replaced. Over the lifetime of the HRS experiment, roughly half of the light pipe columns received these additional squeezes, and in some cases this was done several times for a given column. In retrospect, this practice was over-zealous, since a few of the disks were found to have been squeezed to ~ 1/3 of the original thickness. Remarkably, however, good optical contact was still maintained in such cases because the squeezed silicone material bulged out to the sides of the joint, while still maintaining continuous contact between the flat surfaces.

In the fall of 1986, after the HRS was decommissioned, the 160 photomultiplier assemblies were removed by opening the joints just outside the magnet yoke. All of these disks had good optical transparency, although some appeared to have yellowed slightly. The disks remained flexible and in complete contact with the acrylic pipes, including those that had been severely squeezed. The disks which had not been over-compressed (thickness $\gtrsim 80\%$ of the original thickness) returned to the original shape, but the severely squeezed disks generally had acquired a permanent bulge at their perimeters. In the summer of 1988, a number of seven-year-old disks were extracted from the still undisturbed inner joints. The condition of these disks was found to be similar to the condition of the disks from the outer joints.

The significance of the observed yellowing was assessed by performing measurements of light transmission on both the seven-year-old disks and new disks. The intensity of monochromatic light transmitted through the disks was measured by means of a pyroelectric radiometer. The ratio of transmission through the seven-year-old disks to that of new disks was found to be 0.76 ± 0.03, 0.78 ± 0.03 and 0.83 ± 0.03 at central wavelengths of 400, 433 and 500 nm, respectively. This slight deterioration in light transmission amounted to an average of $\sim 3\%$ per year, although it is not clear whether the change was linear with time. In any case, changes of this magnitude were not significant, or even noticeable, during the actual running of the HRS experiment.

In conclusion, our experience with the silicone disk optical joint was entirely satisfactory. The joints were in continuous use for five years, and could have been used much longer. In an $e^+ e^-$ colliding beam environment a slight yellowing of the silicone was observed, but the increase of light attenuation in a joint was found to be only $\sim 3\%$ per year.

Acknowledgements

We thank W.E. Evans for his valuable assistance in devising techniques and performing tests to determine the optimum procedures for producing our optical disks. This work was supported in part by the US Department of Energy under Contracts DE-AC02-76ER01428 and W-31-109-ENG-38.

References

[1] J.S. Loos et al., Nucl. Instr. and Meth. A249 (1986) 185.
[2] D. Bender et al., Phys. Rev. D30 (1984) 515.