

# Performance Comparison of Flexible Detector Designs

---

**Abstract:** The purpose of this paper is to present test results of recent measurements on a scintillating fill fluid (i.e., liquid scintillator filled) detector and a scintillating fiber bundle detector designs, and explain the observed differences in efficiency. In our measurements we observe an improvement of factor of 2.4 in light output for a fill fluid detector compared to scintillating fiber bundle detector of the same diameter and length.

**Background:** The process measurement marketplace has, for numerous years, used nuclear-based level detectors to measure process levels. Due to their improved sensitivity, scintillation detectors have replaced traditional ion chamber technology in continuous level applications. Scintillation detector designs incorporate either non-organic scintillating crystals such as sodium iodide (NaI) or faster organic plastic scintillation materials as the sensing material. The increased sensitivity came with disadvantages to the user; they are rigid, limited in length to 15 ft (4.6 meters) and heavy. In recent years a new type of scintillation detector has been introduced to the market which can be manufactured in single lengths up to 23 ft (7 meters), is lightweight, and has the ability to contour to the shape of a vessel; hence the term “Flexible Detector”.

There are two designs of Flexible Detector on the market. One approach [1] is based on utilizing liquid scintillator (i.e., fill fluid). The fill fluid is contained in a special, clear, 1” diameter tubing having the proper index of refraction to trap a portion of the light pulses via total internal reflection, guide them along the tubing, and ultimately into the photo-multiplier tube through a glass light guide. A thermal expansion bellows is attached to the bottom to allow for fluid expansion/contraction. The fluid is sealed using O-rings and hydraulic clamping techniques, and placed under a small constant pressure.

The second approach uses a scintillating fiber bundle [2]. The scintillating fibers are not the typical glass fiber-optics used in today’s communications systems. These scintillating fibers are made from a polystyrene-based core with an external acrylic cladding to improve the light trapping efficiency. A second cladding material is often used to improve the trapping efficiency even further. The fibers used in this design are of the 1mm range, and consist of approximately 400 fibers bundled together to form a 1” diameter bundle. This fiber bundle is then coupled to a photomultiplier tube for conversion of detector light pulses to electrical pulses.

The bodies of both detector designs are covered and protected by a flexible conduit.



Figure 1. Scintillating Fill Fluid Flexible Detector

**Detector Parameters:** Two five foot long Flexible Detectors, one of the fill fluid, and one the fiber bundle design were compared. Each detector was a standard production model calibrated by their respective manufacturer.

**Temperature Cycle:** The units were placed inside an environmental chamber and exposed to a constant broad-beam 0.3 mR/hr exposure rate from a CS-137 radioactive source. The temperature was cycled between 0°C to 50°C using a Watlow series F4 controller. Both units performed with a flat response. . (Note: Both units are specified to -20°C)

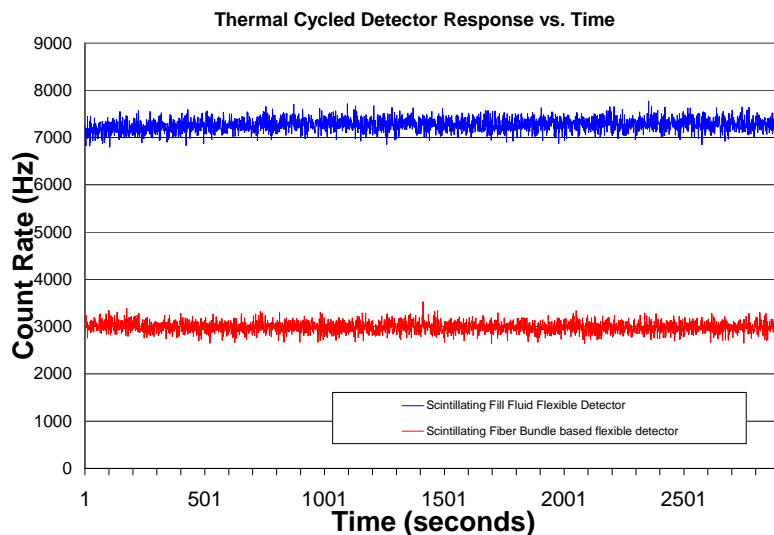


Figure 2. Flexible detector response to temperature variations as a function of time. Data was taken with ~ 0.3 mR/hr exposure rate. Blue trace represents the data for the fill-fluid while the red trace corresponds to the scintillating fiber-bundle detector. The ratio of the average of two data sets is 2.4.

**Radiation Fields:** Both units were exposed to low level exposure rates from 0.05 to 0.9 mR/hr to record their response. Figure 3 shows detector count rate vs. exposure rate plotted on a log scale. The results show the fill fluid scintillator has an output of greater than twice that of the fiber bundle for the range of measured exposures rates.

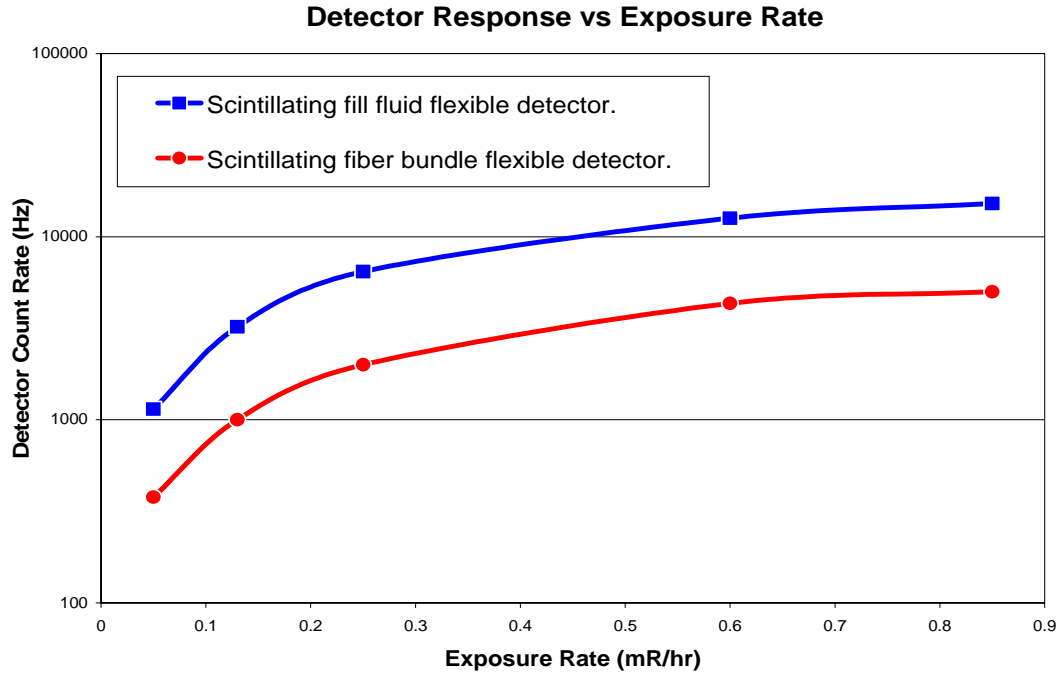


Figure 3. Detector response vs. exposure rate. The solid lines connecting the data point are not trendlines or fits to the data and are inserted to guide the eye. The error bars on the measurements are not shown since the statistical uncertainty on each point (one standard deviation) is smaller than the size of the data labels (typ. ~ 3% -0.8% for fill fluid detector and 5.1%-1.4% for scintillating fiber bundle detector).

To explain this difference in performance one needs to consider three important design features of the scintillating fill fluid detectors.

In what follows the following assumptions are implicit:

- The scintillation spectrum of the fibers and the fill fluid scintillator are similar.
- The Photomultiplier Tube (PMT) quantum efficiencies for both detectors are the same.
- PMT gain and signal thresholds are kept the same for these measurements.
- The light output of the bulk liquid scintillator is similar to the bulk scintillator used in the BCF-12 fiber (i.e., number of photons generated per keV of energy and not including the trapping efficiency).

Given the above assumptions the following are the major reasons for the improved light output:

1. **Larger active volume:** A scintillation liquid filled volume has no dead areas inside the detector fiducial volume defined by the flexible tubing. This is to be compared with the scintillating fiber bundle which has a packing fraction of the fiber bundle as well as the inactive part of the fiber which contribute to lowering the effective active volume (i.e., the cladding and inactive material between the fibers). These two factors contribute greatly to the amount of light which is generated as a result of Compton scattering of gamma rays in the active scintillator.
2. **The amount of direct light:** The solid angle subtended by the PMT in the scintillating fill fluid detector is considerably larger. This allows more direct light (i.e., light that does not get scattered from the core-cladding interface) to reach the PMT.
3. **Smaller critical angle:** Figure 4 shows the definition of the critical scattering angle in both a cladded fiber as well as a fill fluid flexible detector. The critical angle is defined as the minimum angle for which all light rays get trapped in the volume and propagate within the fiber/liquid scintillator detector.

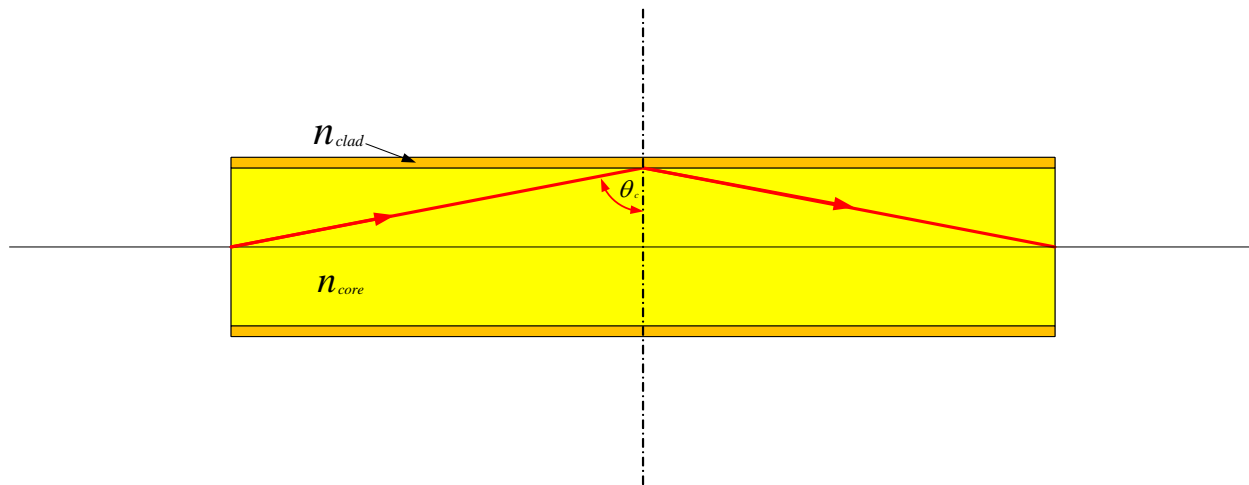


Figure 4. This figure illustrates the geometry of light ray scattering from core-cladding interface at the critical angle for a multimode fiber. All rays with angles larger than critical angle at the interface are trapped and propagate through the fiber. This light trapping mechanism is valid both for a single multimode fiber as well as a liquid scintillator filled tube as described in the text.

The critical angle  $\theta_c$  is given by the expression:  $\theta_c = \sin^{-1} \frac{n_{clad}}{n_{core}}$  where  $n_{core}$  and  $n_{clad}$  refer to the indices of refraction for the respective media. The fill fluid scintillator design could be considered as a large fiber. As such the core refers to the liquid (fill fluid) of the scintillator while the flexible tubing in which it is contained constitutes the cladding. The critical angles for the liquid scintillator detector and the fiber bundle (Bicron/Saint Gobain BCF-12) single clad fibers are 68.6° and 60.6°, respectively.

For an interaction occurring on the symmetry axis of the fiber, one traps all rays with angles smaller than  $90^\circ - \theta_c$ . If one assumes that the scintillation light is emitted uniformly in all directions then we can calculate the amount of light trapped into the fiber (in one direction only). This is given by the ratio of the solid angle subtended by the angles between 0 and  $90^\circ - \theta_c$ . The ratio of the solid angle to  $4\pi$  is the amount of light that would be propagated in one direction (for simplicity we ignore the attenuation of scintillation light due to various absorption processes).

For the fill fluid scintillator detector and the BCF-12 single clad fibers the total trapped light is 3.45% and 3.22%, respectively. This indicates a 7% improvement in the fill fluid scintillator design just from the difference in critical angles.

The above effects combine to improve the light generation and collection efficiency of the fill fluid scintillator over the fiber bundle design by a factor of  $> 2$ .

**Additional Observations:** Acrylic hardens over time and becomes brittle, this combined with flexing may result in “crazing” of the core scintillator and cladding. This will reduce the effective attenuation length of the fiber. In the cladding application, fissures may occur, resulting in light (signal) loss. The hardening process is accelerated under conditions of temperature cycling.

Once acrylic is contoured and becomes brittle, cracking may occur if the unit is removed and straightened.

**Conclusions:** Test results indicate that the light output performance of the fill fluid scintillator design is superior to that of the fiber bundle, measuring greater than twice the output at low radiation fields. This difference in efficiency gives the user significant advantages in terms of cost savings, performance and safety:

1. Lower level activity sources can be used, increasing plant safety and reducing costs.
2. Longer working life of sources can be achieved, reducing the need for disposing of existing sources.

3. Upgrading detectors and electronics on older sources to increase accuracy and reliability. Analogue systems can be updated to your protocol of choice enabling plant integration at minimal cost.
4. Significantly less signal noise at the low levels resulting in more stable and repeatable process variables.
5. Ability to use this detector technology on applications that would otherwise be unachievable.
6. The long term behavior (in particular chemical stability) of the liquid scintillators is well studied in the literature. It has been used extensively in large scale experiments [4-8] . The liquid scintillator used in fill fluid detector is chemical compatible with PTFE as well as glass and other material used in the detector; therefore the reliability and longevity of the fluid filled detector over the recommended temperature range is assured.

### **References:**

- [1] <http://www.ronanmeasure.com/pages/images/Continuous%20Level%20brochure.pdf>
- [2] “Saint Gobain Plastic Scintillating Fibers Brochure”, <http://www.detectors.saint-gobain.com/Media/Documents/S00000000000000001004/SGC%20Scintillating%20Optical%20Fibers%20Brochure%20605.pdf>
- [3] “Nuclear level sensing gauge using scintillating fiber bundle”, USPTO Patent # 6,198,103
- [4] C. Athanassopoulos et. al. , LA-UR-96-1327, submitted to Phys. Rev. C. [LSND Collaboration]
- [5] Proposal for the MiniBooNE experiment: <http://www-boone.fnal.gov/publicpages/proposal.ps>
- [6] K.Inoue, *New J. Phys.* **6**(2004)147. [KamLAND Collaboration]
- [7] [http://arxiv.org/PS\\_cache/hep-ex/pdf/0606/0606025v4.pdf](http://arxiv.org/PS_cache/hep-ex/pdf/0606/0606025v4.pdf) [Double-CHOOZ Experiment]
- [8] “A Precision Measurement of the Neutrino Mixing Angle  $\theta_{13}$  using Reactor Antineutrinos at Daya Bay”, Daya Bay collaboration [arXiv:hep-ex/0701029v1](http://arxiv.org/abs/hep-ex/0701029v1)