TABLE II

Detectability at 100 m in Air

(10-s count, false alarm probability ≤ 0.00135)

	5-cm Ge(Li)		127-cm NaI(Tl)	
	Total	Uncollided	Total	Uncollided
Source gamma/s	8.9×10^8	2.4×10^9	1.3×10^8	5.6×10^8
Plutonium mass (g)	30	79	4.4	19

The NaI is a factor of ~7 better than the Ge(Li) in the total flux mode. In Profio and Huth's original table, the NaI was only a factor of 3 better.

For detector comparison purposes, the problem of whether or not to use Poisson statistics can be circumvented by simply assuming the use of a longer count time or more detectors. For a 1000-s count with a single detector, the Table I detectable masses will decrease by a factor of 10, but the ratios among the individual values will be as listed. Generally, a 1000-s count time is not practical for applications involving area scanning.

The mistakes discussed above do not change the result that counting the total flux is more sensitive than counting only the uncollided flux. However, for the 60-keV uncollided flux case using the Ge(Li) detector, Profio and Huth used an unrealistically wide window of 10 keV. Since the resolution of this type of Ge(Li) detector should be ≤500 eV at 60 keV, a window of 1 keV or less is more realistic. With a 1-keV window and a false alarm probability of 0.00175 (close to the conventional 3σ value of 0.00135), a source strength of 0.35 cps can be detected in a 10-s count. This corresponds to 31 g of plutonium, essentially the same as is calculated for the total flux case (Table II) using the correct Poisson false alarm probabilities. Thus, for a realistic case, the Ge(Li) sensitivities are equivalent for the total flux and uncollided flux cases.

For a 1000-s count with the 1-keV Ge(Li) window at 60 keV, the detectable plutonium mass would be 2.0 g compared to 2.6 g for the total flux case with a 50-keV window. In this case, photopeak counting is somewhat better than the total flux case. Under the same conditions, the larger NaI detector is still superior because a 1000-s count of the total flux gives a sensitivity of 0.44 g. Neither calculation takes into account the effect of the higher energy gamma rays of the plutonium source on the background and signal in this region.

Finally, Profio and Huth conclude that although the NaI detector is 25 times larger than the Ge(Li), its sensitivity is only 3 to 4 times larger. They imply that this means that there is something inherently better about the Ge(Li) compared to the NaI There is nothing magic about this result. Since both detectors have nearly the same efficiency and background per unit area, the only difference in their sensitivities for the total flux case arises from their surface area difference. It is easily shown that detection sensitivity for a fixed count time and source detector geometry is proportional to the square root of the detector area. For these two detectors, the NaI is expected to be a factor of ~5 more sensitive than the Ge(Li) in a mode involving equal windows.

Compare the total count mode sensitivity for the Ge(Li) and the NaI. Assume a count time sufficient to give normal distribution statistics (Table I ratios apply). The ratio is 26/4.4 or ~6. The difference between this factor of 6 and the expected factor of 5 is solely attributed to the different backgrounds used: 0.01 cps/(keV cm^2) for the Ge(Li) and 0.007 cps/(keV cm^2) for the NaI.

The 127-cm^2 NaI detector is clearly superior to the 5-cm^2 Ge(Li) detector for the remote detection scenario. The difference arises almost entirely from the larger surface area of the NaI detector. The inherent low background of the Ge(Li) construction materials is not an advantage in this problem since the detector must be unshielded, or at best, 2π shielded for remote sensing. In this case, the natural background radiation entering the unshielded portion of the detector overwhelms any background arising from detector construction materials.

On a cost basis, the superior performance of the NaI detector will cost ~5 times less than the Ge(Li) (unit cost). For approximately equal sensitivities (equal detection areas), the NaI will cost ~125 times less than the Ge(Li), since 25 Ge(Li) detectors are required to equal a single NaI detector.

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REFERENCE

1. A. E. PROFIO and G. C. HUTH, "Remote Sensing of Plutonium by the Low-Energy Scattered Flux," *Nucl. Technol.*, **26**, 340 (1975).

REPLY TO "COMMENT ON 'REMOTE SENSING OF PLUTONIUM BY THE LOW-ENERGY SCATTERED FLUX' "

Sampson[1] has made a number of corrections and comments on our paper, some of which we agree with and some of which we do not. Many of his "corrections" are based on different assumptions rather than mistakes on our part.

He is correct in pointing out that the captions on Figs. 3 and 5 were reversed. However, the correct flux values were used in our analysis:

Average background count rates were used in some of our detectability calculations. To be consistent, we agree it would be better to use the energy-dependent background data presented in Figs. 12 and 13. But this reduces the minimum detectable source strength and plutonium mass by only 27% for the total flux mode of the 127-cm^2 NaI(Tl) detector (as computed by Sampson). The figures presented in Table III of our paper for the 5-cm^2 Ge(Li) detector should be corrected. The detectability of the 130-keV source would be modified somewhat. Our conclusions are unchanged.

Sampson makes a great deal about using the exact Poisson distribution at very low count rates instead of the square root of the mean. We think it more logical to simply assume a somewhat longer integration time than the arbitrary 10 s in the example. As Sampson points out, the ratios of detectable masses will remain unchanged.

With background assumed constant, sensitivity depends on the window width, which in turn depends on the energy resolution of the Ge(Li) detector. The total flux mode is more sensitive than photopeak counting, at 100 m in air, for window widths >2 keV. The total flux method is considerably more sensitive at greater attenuations, as shown in Fig. 10, for example.

There are actually two major points made in our paper. One has already been discussed: Total flux counting, especially at large attenuations and for low source energies, is more sensitive than detection of the uncollided flux. The second point has to do with the possible superiority of a low-background semiconductor detector over an NaI(Tl) scintillation detector for remote sensing of plutonium. First, the 5-mm-thick Ge(Li) detector is as efficient as the 1.6-mm-thick NaI(Tl) detector for low-energy photons, on an equal area basis, and is superior to the thicker NaI(Tl) sometimes used for sensing of plutonium because of lower background and lower efficiency (hence lower Compton background) for high-energy gamma rays. Second, the intrinsic background is smaller, and even if ambient background is controlling, we think the smaller semiconductor detector is easier to shield over the 2π back hemisphere, at least in terms of smaller mass of shielding (an important consideration in airborne or portable applications).

The sensitivity is also a function of the detector area, which in turn affects the cost. Large area intrinsic and lithium-drifted germanium detectors are being fabricated, and as Sampson mentions, detectors can be grouped in an array. It is true that a thin NaI(Tl) detector is less expensive per square centimeter than germanium, but we feel there are some applications where cost is not the primary consideration.

Finally, we believe that a definitive comparison of the merits of low-energy scattered flux sensing, and comparisons of thin NaI(Tl) and Ge(Li) detectors, would best be done by measurements in the field.

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REFERENCE

1. THOMAS E. SAMPSON, "Comments on 'Remote Sensing of Plutonium by the Low-Energy Scattered Flux,'" *Nucl. Technol.*, **31**, 148 (1976).

ISSS—AN INTEGRATED SAFE SHUTDOWN SYSTEM FOR LIGHT-WATER-REACTOR PLANTS

A preliminary conceptual design is presented for an integrated safe shutdown heat-removal system (ISSS) for light-water reactors that is completely independent of all components and systems outside the primary containment other than the ISSS itself. The system is predicated on execution of reactor trip (scram) and no within-containment loss-of-coolant accident (LOCA) induced by piping failure. It requires ~10 min to activate. It is intended to serve as a backup to the usual shutdown heat removal systems in case of unusual events, including fire, sabotage, and a loss of currently provided ac or dc power.

The system has evolved from a goal of achieving simplicity with respect to process and physical layout, as distinct from the large capacity, complex, multipurpose systems that now perform this relatively unsophisticated, small-capacity, but absolutely essential cooling function after reactor trip. Some of the complexities introduced into current designs are a direct result of setting difficult design objectives, such as automatic response to piping and power failures. As a result, the reliability of performing this critical and simple but more frequently needed function can be reduced. And in a physical-layout sense, the current systems for performing post-scram cooling functions are broadly exposed to a large variety of potentially disabling accidents and to sabotage. A main purpose of the ISSS is to minimize such exposure.

The ISSS is normally "dead" or insensitive without direct operator action. It does not depend on any electrical, pneumatic, or hydraulic control system nor on any water supply or steam release system not integral with ISSS.

The major elements of the ISSS are to be housed in a satellite structure or bunker, preferably in an underground configuration. The bunker would be thoroughly protected against environmental hazards and unauthorized entry. The ISSS would have its own integral stored water and fuel supplies. Fuel requirements would be in the range of one-twentieth of the usual diesel fuel storage.

Some of the piping and valves would be within primary containment. Some isolation valves might be dispersed within auxiliary buildings or secondary containments, but in all cases redundant valves would be within primary containment. Figure 1 illustrates one conceptual layout of the ISSS.

For pressurized water reactors (PWRs), natural convection would be used to carry heat to the normal steam generators, using the safety-relief valves (modified as necessary) for secondary steam relief. The ISSS would include independent pressurizer and steam generator level indication, and independent electric-motor-driven manually activated feedwater pumps supplying water to existing feedwater headers. The ISSS would have the ability to positively isolate any lines running outside the containment that might offer a path for undesired through-line coolant inventory loss. Failure during test of the ISSS elements by pipe rupture, equipment failure, or otherwise would not prevent the functioning of equipment currently provided for the emergency core cooling system. The PWR primary