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In Vivo Detection, Localization, and Measurement of
Radionuclides in Man: A Detection System for the
Localization and Measurement of Small Amounts of
Photon Emitters

Progress Report: Contract EP-78-S-02-4957
for period September 1, 1978 - May 15, 1979

and

Proposal for Continuation of Research
September 1, 1979 - August 31, 1980

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SYNOPSIS OF PROJECT

Summary

The objectives of this research include the design, construction and testing of a photon detection system which will yield, simultaneously, information proportional to both the magnitude and location of sources of radioactivity. The operating principle of the detector system, "active collimation", allows spatial resolution by utilizing the crystal elements themselves as the collimating device; hence a greater counting efficiency is attainable than with other currently available systems. The differences in characteristics of various crystals are utilized as the means of separating events occurring in each of five crystals (see Figures 3,4,5,6). Mathematical processing of the counts from the individual crystals is then employed in conjunction with their geometric relationship to develop both positional data and to quantify the amount of radioactivity.

The results of experimentation to date have led to promising new approaches. By utilizing crystal detector elements in a "active collimation" configuration and incorporating them in an array which permits these crystals to be alternately advanced and retracted in a programmed, ordered manner, a high degree of spatial resolution is believed achievable without unduly compromising system sensitivity. A series of experiments have been planned with

a detector of optimized design to provide data as to the ultimate performance that can be achieved with an N-element detector array. The experiments include development of the optimal crystal configuration, studies to ascertain the most efficient crystal shape in terms of optical properties and intrinsic resolution, and the evolving of data processing techniques to translate detector response into precise source position information for localization or imaging purposes.

Significance

There is wide-ranging potential importance for a system capable of accurately defining the location of low level radiation sources. One application would be the localization of inadvertently ingested or inhaled radionuclides within the body for dosimetric purposes. Moreover, because of the considerably improved resolution-to-activity factor believed achievable, there is promise for this system in nuclear medicine as well. Good imaging should be obtainable with much lower radiation exposure levels than is possible with present methods.

Yet another use of this approach would involve surveillance or monitoring of the environment, namely the detection and localization of radioactive plumes or clouds in the atmosphere. N-element detector arrays could be constructed in a manner similar to the unit developed here that would define the outline and ascertain the location of radionuclide-

bearing air masses in the atmosphere, as might result from accidental emission by a nuclear facility.

Extra-galactic X-ray emanation sources might also be located by suitable N-element detector arrays which would function in a manner analogous to a radio telescope.

In Vivo Detection, Localization, and Measurement of
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Localization and Measurement of Small Amounts of
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A. Introduction

1. Objective:

The purpose of this research is the design, construction and testing of a photon detection system which will yield, simultaneously, information proportional to both the magnitude and the site(s) of deposition of radioactivity accidentally inhaled or ingested or otherwise deposited in the body. The operating principle of the detector system, "active collimation," allows spatial resolution without the use of separate collimating devices and, hence, with a greater counting efficiency than other currently available systems.

2. Background:

Whole body in vivo detection systems for the quantitative assessment of body burdens or organ burdens of radionuclides and subsequent radiation dose determination depend on knowledge of the distribution of the nuclide in the body. In the case of more hazardous nuclides like the transuranics, treatment of the contaminated individual may rest on the accuracy of the estimate. At the present time, in vivo measurements of lung burdens of the nuclides, ^{238}Pu , ^{239}Pu and/or ^{241}Am in man are accomplished by detection and measurement of the low

energy photons which they emit using either large area gas proportional counters or NaI-CsI, dual-crystal scintillation detectors positioned anterior to the thorax. Calibration factors are usually determined by measuring the activity of a tissue-equivalent torso surrogate containing a known quantity of the radionuclide, usually distributed uniformly throughout mock lung material. It is generally conceded, however, that this may not be the way this material is actually distributed and that it does, in fact, concentrate with time in certain tissues such as the lymph nodes, depending on factors such as chemical form, solubility, particle size, etc. In any case, the distribution would probably be complex and, since bioassay measurements may be even more uncertain in terms of arriving at a body or lung burden, it is essential to refine the in vivo photon counting technique. To obtain the best calibration factor relating external counting rate to internal burden, experimental knowledge of isotope distribution is necessary. It is essential, therefore, to design and construct a system which can adequately determine not only the magnitude but also the sites of deposition of internally-deposited material.

At present, sites of internally-deposited radioactive materials, such as those necessitated by prescribed medical diagnostic procedures, are delineated with the use of scintillation cameras or other devices which may remain stationary or scan the whole body or organ of interest in a rectilinear fashion (1,2,3). These devices provide an image of the site

of deposition of the isotope with the use of NaI crystals and external collimators of various configurations, i.e., pinhole, multichannel (parallel or focusing), or slit, made of lead or some other high Z material. The requirement of a collimator to form an image of the photon emitter and to obtain good resolution between an area of deposition and an adjacent area of no deposition restricts the geometric counting efficiency of these devices. This restriction requires that relatively large amounts of radioactivity be given to the subject in the diagnostic procedures and limits the usefulness of these devices for the location of accidentally ingested or inhaled radioactive nuclides. Low-level amounts of these nuclides that may present a serious, long-term health hazard to the individual might not have sufficient activity to yield a statistically reliable signal in terms of spatial resolution.

Recently, the use of ultra-pure germanium diodes in imaging systems (4,5) has indicated the possibility of improved resolution over the scintillation crystal-phototube system because of the greater energy resolution of the Ge diodes. This improved energy resolution allows better discrimination against Compton events which occur in the detector assembly as well as tissue. Instead of using a phototube to signal where an interaction has taken place, as with a NaI crystal, the Ge devices use parallel grooves cut into the n and p faces, with the n face grooves oriented 90° with respect to the p face grooves, thus forming an orthogonal

system from which signals proportional to the location of an event in the detector are obtained. As with the gamma camera, however, a collimator is still necessary to locate and form an image of a source of photons in space. The operating principle of the proposed device, "active collimation", allows the construction of a detector capable of resolving the shape and location in space of a source of photons, but without the geometrical restrictions imposed by the need for pinhole or other collimating devices made of lead or some other inactive material. Thus, the instrument may have potential usefulness in nuclear medicine as an imaging device which will function at lower radiation doses to the patient as a result of the elimination of the collimator, as well as in the health physics application of determining the magnitude and site of deposition of accidentally deposited radioactivity.

3. Rationale:

Dual crystal systems of NaI-CsI, utilizing pulse-shape discrimination, accomplish a reduction in low energy background due to Compton scattered events as well as a reduction in room background, making possible the measurement in vivo of small amounts of radionuclides which emit photons in the energy range below 100 kev. Prior to the advent of the dual crystal technique, low level in vivo determination of nuclides emitting photons in this energy range (uranium, transuranic nuclides, ^{210}Pb , etc.) had been difficult and statistically unreliable because of the high background count rates obtained.

Many laboratories now use dual-crystal systems in their whole-body counters on a routine basis to screen personnel handling transuranic material. The design, construction, and the first use of these systems for in vivo measurements of low-energy emitters was accomplished at this laboratory several years ago (6,7,8,9,10). In these systems, pulse-shape discrimination, based on the difference in photomultiplier output pulse shapes of the light from the NaI and CsI crystal materials, is used to gate anti-coincidence circuitry and eliminate from pulse height analysis those Compton interactions in the thin, primary NaI detector which result in forward scattered photons that also interact in the secondary CsI crystal. Figure 1 shows a cross-section of the dual crystal detector as well as the output pulse shape and a block diagram of the detection and measurement system used.

The active collimation principle also utilized pulse shape discrimination. For this application, however, the crystals are oriented differently with respect to each other and with respect to the photomultiplier tube. The principle of active collimation and the basic operating details of the detection system may be seen in Figures 2, 3, 4 and 5.

Figure 2 shows the plan and elevation views of a single detector element out of an N-element array. Each detector element consists of five interspersed crystals of NaI(Tl) and CsI(Tl and Na), each L inches long and W inches wide (W_{Na} , w_{Cs}) such that the five crystals make up a square configuration. The thicknesses (T_{Na} , t_{Cs}), while not related in any fixed manner,

may be used with the parameters W, w , to optimize the detector dimensions for a specific photon energy range, resolution and/or degree of collimation.

Figure 3 is a top and side view of the detector element shown without PM tube or light pipe for simplification. A point source of photons is centered beneath it. With the source at the center of the crystal array as shown, interactions will occur in the NaI(Tl), the CsI(Tl), and the CsI(Na) individually, and as a result of Compton scattering interactions, in adjacent crystals of NaI and CsI simultaneously. With the use of pulse shape discrimination, however, it is possible to obtain an output signal from the detector for the NaI interactions alone, $S_{\text{NaI(Tl)}}^*$, the CsI alone, $S_{\text{CsI(Tl)}}^*$ and $S_{\text{CsI(Na)}}^*$, and reject those that occur simultaneously in any two or more crystal elements. Thus, it is possible to establish three ratios, $S_{\text{NaI(Tl)}}/S_{\text{CsI(Tl)}}$, $S_{\text{NaI(Tl)}}/S_{\text{CsI(Na)}}$, and $S_{\text{CsI(Na)}}/S_{\text{CsI(Tl)}}$, that describe source position. Moreover, as shown in Figure 4, movement of the detector element along the X axis will cause the ratios $S_{\text{NaI(Tl)}}(X)/S_{\text{CsI(Tl)}}(X)$, $S_{\text{NaI(Tl)}}(X)/S_{\text{CsI(Na)}}(X)$, and $S_{\text{CsI(Na)}}(X)/S_{\text{CsI(Tl)}}(X)$ to change. The magnitude of the change will be different for each ratio and will depend on the direction of motion and the total distance moved.

It follows that these ratios may be obtained in the Y axis direction also by turning the detector element through 90° , establishing the magnitude of change as the detector moves

* In subsequent discussion, $S_{\text{NaI(Tl)}}$ will be referred to as R_3 or R_4 , depending on which NaI crystal, i.e., central or outer, is involved. Similarly, $S_{\text{CsI(Tl)}}$ is designated as R_1 , $S_{\text{CsI(Na)}}$ as R_2 .

along that axis. Thus, using a single detector element and moving it incrementally along the X and Y axes, it is possible to resolve the position of a point source in the X-Z and Y-Z planes or to trace the outline of an organ or the area in which deposition of radioactivity, accidental or deliberate, has occurred. The detector element, therefore, would be behaving in the same manner as a single crystal detector with a slit collimator, but with a significant difference, i.e., the total amount of signal available. By pulse shape discrimination, the ratio $S_{\text{NaI}}/S_{\text{CsI}}$ is obtained; however, the sum $S_{\text{NaI}} + S_{\text{CsI}}$ is also obtained and, in terms of the signal available for assessing how much total radioactivity is present at the site of deposition, the detector element acts as a single crystal without a collimator. Hence, with the use of "active collimation", it will be possible to construct a photon detector which will operate in two modes simultaneously, as a detector with a collimator for spatial resolution, and as a detector without a collimator for optimum detection efficiency.

N-Element Array: Although the single detector element could be moved along the X-axis and the Y-axis as described above, the same data may be obtained by positioning several detector elements in an array as indicated in Figure 5. In the array, the detector elements are placed side by side, but with their axes turned 90° with respect to each other. In this manner, the signals from detector elements a, b, c... etc. would define Y-axis position for that row, while elements 1, 2, 3...etc. would define X-axis position for the same row. In a like manner, X-axis oriented detector elements would

define Y-axis position along columns a, b, c...etc., and Y-axis oriented elements would define X-axis position along columns 1, 2, 3...etc. In terms of its signal output, the array of N elements may thus be pictured as a single detector element being moved into each of the individual positions in the array, with the signal ratios $S_{\text{NaI(Tl)}}(X)/S_{\text{CsI(Tl)}}(X)$, $S_{\text{NaI(Tl)}}(X)/S_{\text{CsI(Na)}}(X)$, $S_{\text{CsI(Na)}}(X)/S_{\text{CsI(Tl)}}(X)$, and $S_{\text{NaI(Tl)}}(Y)/S_{\text{CsI(Tl)}}(Y)$, $S_{\text{NaI(Tl)}}(Y)/S_{\text{CsI(Na)}}(Y)$, $S_{\text{CsI(Na)}}(Y)/S_{\text{CsI(Tl)}}(Y)$, changing at each position. In terms of the array, the output is a gradation in magnitude of the X-axis and Y-axis ratios along the respective rows and columns of elements -- with the gradation in turn dependent on the geometry of the radioactive deposition, i.e., point source, line source, area source, etc. The array will thus provide 3·n signals (3 for each element) to define source position in the X-Z and Y-Z planes, and at the same time give $S_{\text{NaI}} + S_{\text{CsI}}$ for magnitude determination using the total counts obtained from all elements.

Prototype Detector Element -- Preliminary Results: To test the validity of our design rationale, a single prototype detector element was constructed to our specifications,* as shown in Figure 7. Dimensions of the individual crystals for this prototype were based on symmetry and the 1.5 inch diameter PM tube only. Unfortunately, the crystal was accidentally misconstructed with two interspersed CsI(Tl) elements rather than a CsI(Tl) and a CsI(Na) as requested. Nevertheless, it still served to test the operating principle and gives indication of the potential spatial resolution of this design.

* Harshaw Chemical Co., Crystal and Solid State Division, Cleveland, Ohio.

To test the operation of the element, a 1 mm diameter source of gamma radiation (Cd-109, 88 keV with the 22 keV X-ray filtered) was used, both collimated and uncollimated. These preliminary tests were performed without the use of pulse shape discrimination, unnecessary because of the single gamma-ray energy and relatively high count rates involved, eliminating background corrections.

Figures 8, 9 and 10 are the spectra obtained when the collimated source is moved across the face of the detector element. In Figure 8, the source is centered on the CsI(Tl) crystal and the peak energy (X-axis) corresponds to the light output of that crystal element. The source was then placed approximately midway between one of the CsI(Tl) and NaI(Tl) pairs and the resultant spectrum, shown in Figure 9, contains two peaks -- both 88 keV -- with one representing the CsI(Tl) output, as in Figure 8, and the other NaI(Tl), whose light output per unit energy deposited is about four times that of CsI(Tl). Finally, in Figure 10 the source has been moved to the center of the NaI(Tl) crystal, resulting in a single peak corresponding to the NaI(Tl) output alone.

As the source is moved with respect to the detector, the count rates in the individual crystal change; and the ratio of the integral of these counts., e.g., Σ (CsI counts)/ Σ (NaI counts), also changes. A plot of the ratio as a function of the indicated motion of the collimated source is shown in Figure 11, along with a drawing to illustrate the geometric configuration of the test. The ratio, normalized to one at

the center line of the CsI(Tl) crystal, decreases by a factor of 100 over a distance of 5 mm.

The response to the prototype element to an uncollimated source is shown in Figure 12. The conditions of the measurement are also indicated. The Bi absorber in front of one pair of NaI-CsI crystals was necessary to simulate what would be expected with only a single CsI(Tl) crystal, since the other should be CsI(Na) and hence not contribute to the CsI(Tl)/NaI(Tl) ratio. This resulted in the loss of part of the NaI(Tl) signal as well. The ratio, again normalized to one, was obtained by moving the source from the center line of the CsI(Tl) crystal as indicated, at distances of 5, 10, 15 and 20 cm from the face of the detector.

As expected, the ratio changes with source position along the Z axis, normal to the face of the detector, as well as the parallel axis. Thus for any given position along the X or Y axis, the ratio would be a changing function of the position along the Z axis and the source location could not be determined with a single ratio. When the crystal construction is corrected, however, i.e., the second CsI(Tl) replaced by CsI(Na), the ratios CsI(Na)/NaI(Tl) and CsI(Na)/CsI(Tl) will also be obtained simultaneously with CsI(Tl)/NaI(Tl), and thus provide three bits of information on the location of the source in the X,Z plane or the Y,Z plane.

From the geometry of the prototype element as shown in the figure, the spatial resolution may be altered by either decreasing the width of the CsI(Tl) crystal (W_{Cs}) or increasing

the width of the NaI(Tl) crystal (W_{Na}), or both, as well as changing T_{Na} to T_{Cs} , or both.

B. Progress Report

1. Period: October 1, 1978 through May 15, 1979
2. Summary: Progress obtained thus far is briefly described in the following items:

- i. Rebuilding the detector element to include the CsI(Na) crystal originally left out, with reflector material between the crystal faces yields four peaks for use in obtaining position-sensitive data rather than three as originally expected. The fourth peak is attributable to light loss in the system and is controlled by the area of the crystal subtended by the PM tube. Further, by an appropriate masking technique, it appears feasible to obtain five separate peaks.
- ii. Correction factors have been determined for use in a series of four simultaneous equations to obtain the true net counts under the peaks after subtraction of room background. The "K" factors account for the contributions to each crystal's spectral region from all the others, due to Cs and I escape photons and Compton scatter.
- iii. Multiple-products (rather than ratios) taken of the individual regions (i.e., integral counts under each peak) appear to offer enhanced resolution and sensitivity to changes in source position and in addition, produce a symmetrical product peak at the center of the detector

whereas individual crystal responses, and some ratios, are broad, oddly shaped, and off-center as a result of the position of each crystal in the detector. The results thus far obtained indicate that more useful data would be obtained from three recessed and two non-recessed crystals. Prototype element #2 (Mod II) will be designed on this basis.

iv. A Nuclear Chicago Pho-Dot scanner mechanism has been acquired on a loan basis and put into working order. This unit, which will automatically move the detector over the source in an X-Y scanning motion is being modified to provide automatic data collection in increments of 1-2 mm over a 20 x 20 cm field. This will allow the collection and analysis of highly refined positional data by utilizing long term runs not otherwise feasible with manual data collection.

v. Experiments performed on a 2.5 mm wide NaI crystal -- one-third the 7.5 mm width of the crystals in the prototype detector element -- showed significant loss of resolution at this dimension. The resolution of the 7.5 mm-wide NaI crystal was 15% for the 88 keV ^{109}Cd gamma ray; for the 2.5 mm-wide NaI crystal, the resolution of this peak was 40% fwhm. Furthermore, the resolution changes as a function of interaction location in the crystal. This information will be used in determining a lower limit for the width of the crystals used in prototype Mod II.

3. Report:

The initial phase of this project involved determination of primary detector characteristics, including the spatial and intrinsic resolution of each crystal, as well as detector response to positional changes of a point source.

A snug, sturdy support for the detector-photomultiplier assembly was provided by pouring expanding polyurethane around the unit, resulting in a flat-sided package. This was then sheathed in successive layers of copper and cadmium, to eliminate lead fluorescence X-rays, and the whole assembly was enveloped in lead. To prevent photons scattering off the lead from impinging on the detector, the front aperture was surrounded by a 3/4" lead-cadmium-copper laminated shield.

The shielded detector-photomultiplier assembly was then mounted on a screw jack to permit varying its height, and the jack itself was secured to a 3/4" plywood base. In front of the detector and extending laterally with respect to its central axis, a rack and pinion unit was secured to the plywood. An identical rack and pinion was mounted perpendicularly onto the pinion of the horizontally-positioned rack, thereby facilitating X and Y positioning of a source in front of the detector. Detector-to-source separation distance, Z, could readily be changed by an adjustment screw device attached to the vertical rack and pinion.

A ^{109}Cd ($\gamma = 88 \text{ keV}$) source, sheathed with 0.6 mm copper to filter out the 22 keV Ag X-ray, was placed in a block of

bismuth 1 x 4.5 x 2 cm in which a 0.75 mm collimation aperture has been drilled. The response of each of the crystals comprising the detector was measured by moving the finely collimated source incrementally across its face. Figure 13 is a plot of the peak thus obtained for the CsI(Tl). The full width at half maximum (FWHM)* of the response of each crystal is approximately 7.5 mm. This was expected since, with a well-collimated source, the response should fall to about 1/2 of maximum at the edge of the crystals, all of which are nominally 0.3 in. or 7.62 mm wide. The results are thus well within the reset error of our rack and pinion system, approximately 1.5 mm. These measurements served as base-line measurements to assure that the crystals were all the same 7.6 mm-wide dimension, as well as checking the uniformity of center-line to center-line distances between crystals. The center-line of the centrally-located NaI(Tl) crystal was established as a frame of reference for all point source measurements.

Illumination with an uncollimated source placed over the detector center-line results in the spectrum displayed in Fig. 14. Each crystal produces a peak that was displaced with reference to the central NaI(Tl) crystal, the degree of displacement depending upon a number of factors, viz.: 1) light decay characteristics of each crystal material; 2) photon-to-

* FWHM (capitalized) in this instance is in units of mm and therefore refers to spatial resolution. When referring to the intrinsic, spectral or peak resolution of a crystal, fwhm (lower case) is dimensionless and generally given as percent.

scintillation conversion efficiency; 3) wavelength of maximum emission; 4) integration time constant of amplifier; 5) fraction of the crystal face covered by the PM photocathode. The first four factors influence pulse-shape and/or are utilized in pulse-shape discrimination. They account for the displacement of the first two peaks -- CsI(Tl) and CsI(Na) respectively -- with reference to the central NaI(Tl) output, the fourth or last peak in the spectrum. The cross-section of the central NaI crystal in the detector array is fully encompassed by the PM photocathode, thereby resulting in the highest PM output for the 88 keV events. However, the two edge NaI crystals are so positioned that their cross-sections are not fully circumscribed by the circular PM cathode face (see Figure 7), resulting in a somewhat lower PM output for the same energy deposition. This produces a downward shift in the spectral display of the two end crystals, whose peaks are superimposed since the crystals are positioned symmetrically about the PM tube central axes and results in the third peak.

Responses of the individual crystals, (CsI(Tl), CsI(Na) and the center NaI(Tl) to the collimated ^{109}Cd are shown superimposed in Fig. 15 and are characterized by peak resolutions of 47%, 27% and 15% fwhm, respectively. By comparison, the same source directed at the 15 cm diameter x 3 mm thick NaI crystal of our dual-crystal assembly and at our 20 cm diameter x 10 cm thick NaI crystal yielded spectral peaks of 18% fwhm for both. The apparent improvement in NaI resolution from 18% to 15% may or may not be significant: however, it does

indicate that there is no loss in resolution as a result of coupling the PM tube to the narrow end of the 7.5 mm wide crystal.

Intrinsic spectral resolution as a function of crystal width is an important parameter because of the role this dimension plays in the ultimate spatial resolution of the device. To determine the variation of this parameter, we obtained a NaI(Tl) crystal of the same length and height as the prototype, i.e., 38 mm x 38 mm, but with a width of 2.5 mm -- 1/3 of the prototype 7.5 mm. This crystal was furnished with a demountable PM tube to allow masking of the coupled end, thus incrementally reducing the light output, so that the effect of this variable pulse height and resolution could be determined. The results are shown in Figs. 16, 17, 18 and 19. Fig. 16 is the spectrum obtained with the collimated ^{109}Cd source centered on the 2.5 mm face of the crystal, and the resolution of 40% fwhm is significantly poorer than the 15% value obtained with the 7.5 mm crystal. The results of directing the source at the 38 x 38 mm side of the crystal at various points along the central axis are shown in Fig. 17. As indicated by the position of the peak channel of each of the spectra, PM output pulse height changes as a function of interaction position in the crystal. Since pulse height is proportional to the amount of light reaching the PM photocathode, these results indicate that some light is being lost, probably through internal reflection, as the point of interaction moves further from the photocathode. However, the effect of interaction distance from the photocathode

on spectral resolution is much less pronounced. As shown, the fwhm of the peaks averages approximately 32%, ranging from 30% to 34%. Pulse height variations with interaction site when the crystal is exposed with an uncollimated source will result in peak broadening, however, and an apparent loss of resolution. This is shown in the plots of Figure 18 where the broad face of the crystal was exposed to an uncollimated source. The "crystal face open" curve is thus seen to be the envelope of the discrete peaks of Figure 16 obtained with the collimated source. The other curves were obtained by shielding half the crystal at a time with a thick Bi absorber, 40 mm x 20 mm. When the outer half is shielded, those interactions taking place near the photocathode result in a gradation of large pulses but a still larger number result in broadened pulses due to that portion of the light having longer path lengths. The spectrum obtained when the inner half of the crystal is shielded appears to be the result of light travelling half the length of the crystal, or further, resulting in a more gaussian pulse height distribution and none of the interactions result in large amounts of light reaching the PM. Figure 19 shows the effect of positioning the source at points along the vertical axis of the crystal's broad face, the influence on pulse height appearing much less pronounced. It should be noted that the apparent difference in resolution obtained by situating the collimated source at the front face (40%) and at the side face ($\sim$ 32%) is believed due to the thickness of the crystal. Since the path length ($1/\mu$) in NaI is 5.8 mm for 90% of the

88 kev photons, directing the source at the side of the 2.5 mm crystal results in a narrower pulse height distribution than is the case when the source is directed at the front face, where a greater depth for interaction is available and a range of light paths are provided.

The spectrum of Figure 18, obtained with the inner half of the crystal shielded, is analogous to the characteristics expected from a promontory crystal in the detector assembly where the inner half is effectively shielded by recessed crystals. Although not as serious as when the entire crystal is exposed, the loss of resolution by the narrower 2.5 mm crystal, 40% as compared to the fwhm of 15% of the 7.5 mm wide crystal, will be an important factor in determining the design limit for prototype Mod II.

In addition to ordinary background, derived from sources outside of the detector, spurious spectral interferences result from various events within the crystals themselves, secondary to photon detection. Because crystals are in close proximity, and their respective responses are conveyed to a common PM, escape peaks, iodine and cesium fluorescence X-rays, and Compton scatter from any one of the crystals contribute to the overall spectral display. Counts resulting from these effects will appear in energy regions associated with other crystals, due to the common PM tube and combined spectrum presentation. When this effect became apparent, after analysis of preliminary data, a method was evolved to correct the raw counts derived from each region, using a correction factor, K , that accounts for the fraction of counts spuriously appearing

in an energy region as a result of interference from the other crystals.

The K values were derived by selectively illuminating each crystal by itself with the uncollimated ^{109}Cd source, and determining the number of statistically significant spurious counts observed in the other crystals, whose sole output should have been background as they received no direct photon illumination. Ratios of interference contribution were then developed for each crystal as a fraction of the counts measured in the illuminated crystal, predicated on the premise that an average value can provide the necessary correction. This appears to be a correct assumption. Counts from a point source are then processed in a 4×4 matrix as follows:

$$C_{R1} = K_{1/1}C_1 + K_{1/2}C_2 + K_{1/3}C_3 + K_{1/4}C_4$$

$$C_{R2} = K_{2/1}C_1 + K_{2/2}C_2 + K_{2/3}C_3 + K_{2/4}C_4$$

$$C_{R3} = K_{3/1}C_1 + K_{3/2}C_2 + K_{3/3}C_3 + K_{3/4}C_4$$

$$C_{R4} = K_{4/1}C_1 + K_{4/2}C_2 + K_{4/3}C_3 + K_{4/4}C_4$$

C_R values are the gross counts measured by each respective crystal, C_1 - C_4 are the K -corrected values to be determined, and $K_{1/2}$, etc., are read as "spurious counts appearing in the total for crystal #1 as a fraction of crystal #2 counts when crystal #2 alone is illuminated.

These simultaneous equations are solved for each data point to derive the true count total for a given crystal. To minimize effect of inter crystal overlap at low count regions around the base of a spectrum, only the top half, surrounding a spectral peak, is being used initially as the region of interest for counting purposes.

In the next phase, data were obtained for various positions of the uncollimated ^{109}Cd point source (approximately 1 mm diam.) in a plane 10 cm from the detector face. Supported in a fixture produced from very low density expanded polyurethane, to minimize scatter, the source is initially aligned with the center of the detector at the beginning of each data run, and a 200-second count is taken. Amplifier gain is checked with reference to both the middle NaI crystal and a mercury-relay pulser, which provides a sharply-delineated reference at the low end of the spectral display, just below the CsI(Tl) peak. Ultimately, the pulser will be used as part of an automatic zero shift and gain compensation package that is to be added to the pulse-height analyzer, but to date these corrections have been performed manually at the beginning of each data run and checked at the conclusion.

- An X-coordinate range of 7 cm either side of the detector center was scanned in 1 cm steps. The Y-coordinate field was 3 cm above and below the detector center-line, also scanned in 1 cm steps. These relatively large steps were taken initially to provide an immediate overview of detector behavior and spatial resolution. Facilities are being developed to obtain more precise measurements, over much smaller increments, which will be described later.

Data from the planar array of points, after K correction using the simultaneous equation solution already described, is further processed by generating ratio and product terms from the net count-per-second values derived from each crystal's

region of interest. Initial interest was centered on the ratio terms obtained from detector output, and routines were programmed to develop all six ratios of interest, in addition to a like number of normalized terms. Normalization refers each ratio to a reference ratio obtained when the source is at a central position. Figure 20 shows plots of R_1 and R_2 , the response of the two recessed CsI crystals, R_4 , the central promontory NaI, and R_3 , the response of the two outer promontory NaI crystals -- all as a function of source (uncollimated) displacement from the detector center-line. Also shown are plots of the ratios, R_2/R_1 and R_3/R_2 . The recessed crystals produced broad peaks (FWHM $\approx$ 6 cm) while the promontory crystals produce archlike, bi-modal responses with less-pronounced peaks. Only two of the six possible ratio terms are shown. Of the remainder, i.e., R_3/R_1 , R_4/R_2 , R_4/R_1 and R_4/R_3 , the ratio R_4/R_3 may be discarded because of the broadness of the R_4 and R_3 responses. R_3/R_1 would appear the same as R_3/R_2 but with its node symmetrically displaced on the opposite side of the detector center-line. R_4/R_2 and R_4/R_1 are much broader than R_3/R_1 , R_3/R_2 , with nodes at the same positions, since this aspect of the ratio with R_4 or R_3 is dictated by the peak locations of R_2 and R_1 . Due to the broad and rather constant response of the promontory crystals, the ratios are dominated by the response of the recessed crystals. The plots shown are from data which does not include the improved K-corrected response of the individual crystals. The K-corrected counts of the recessed crystals now go to zero at the points where they are

effectively shielded from the source by the promontory crystals, and the K-correction narrows the response of these crystals, as well as their ratios. Because of the broad peaks produced by ratios and the awkward ratio values that resulted as the divisor response approached zero, alternate approaches to data reduction were explored.

Since division resulted in peak degradation, investigation turned to mathematical treatment that would produce the opposite effect. This resulted in development of product and multiproduct exponentialized terms which, interestingly, produces exalted peaks of enhanced sharpness and symmetry, thereby greatly improving the spatial resolution characteristic beyond that obtained from untreated contributing detector crystal data. Product terms, like ratios, result in root-mean-square error terms that do not severely affect the integrity of the derived position information.

Data processed in product form produces the responses depicted in Figure 21. As with the ratios, the peaks of the product responses of R_1 and R_2 with R_3 and R_4 are dictated by the responses of the recessed crystals, and are displaced symmetrically about the detector center-line. Product $R_1 R_2$ peaks at the center-line of the detector, although the individual responses, R_1 and R_2 , peak on either side of the centerline. This result led to the plot in Figure 22, in which the response of the multiple product $R_1 \cdot R_3 \times R_2 \cdot R_3$ is also shown to peak at the detector center-line while the individual products, $R_1 \cdot R_3$ and $R_2 \cdot R_3$ (Figure 21) peak on either side of the

center-line. The multiple product response is thus seen to be the product of $R_1 \cdot R_2 \times R_3^2$, i.e., the individual product response $R_1 \cdot R_2$ multiplied by a more or less constant term R_3 , which has a broad, less pronounced bimodal response. There is an enhancement of spatial resolution because of the product $R_1 \cdot R_2$ is narrower than either R_1 or R_2 , and more closely straddles the center-line than does either of the individual responses. The resolution of the product $R_1 \cdot R_2$ is approximately 3.5 cm as compared to the individual resolutions of about 6 cm each. Because R_3 is approximately constant, the successive multiple product development does not affect resolution any further. It can, however, have a most substantial effect on the steepness of the response, and when the multiple product development includes additional recessed crystal products, whose slopes are changing with source position, still further improvement of the resultant peak is realized.

To test this, the responses of the individual crystals were used to develop the multiple product response of a detector element constructed as shown in Figure 23, which has 3 recessed crystals (R_1 , R_3 and R_5) and two promontory crystals (R_2 and R_4), the reverse configuration of the prototype element. From the above discussion and the product development of Figures 20, 21 and 22, it follows that the products $R_1 \cdot R_3$ and $R_3 \cdot R_5$ will produce peaks centered over detectors 2 and 4, respectively, and the multiple product $(R_1 \cdot R_3)(R_3 \cdot R_5)$ will produce a peak centered over detector 3. In this case,

however, R_3 is not constant and the multiple product does enhance resolution. As shown in Figure 24, the FWHM of $R_1 \cdot R_3$ is about 3.5 cm. The multiple product $(R_1 \cdot R_3)(R_3 \cdot R_5)$, however, now has a resolution of approximately 2.2 cm. A third product may now be factored in, viz., $R_1 \cdot R_5$ which, because of the zero points of the individual responses, will have its peak also centered over crystal 3 but be lower in magnitude than $(R_1 \cdot R_3)(R_3 \cdot R_5)$. The third curve is the response of $(R_1 \cdot R_3)(R_3 \cdot R_5)(R_1 \cdot R_5)$ or $R_1^2 \cdot R_3^2 \cdot R_5^2$. The FWHM has not improved since $R_1 \cdot R_5$ has about the same resolution as $(R_1 \cdot R_3)(R_3 \cdot R_5)$. Note, however, the change in slope as measured between 2 and 3 cm from the center-line.

Although not shown, each individual crystal in that region of its response has a count change ratio of 1.3, whereas the product of two of these individual responses increases this change ratio as shown to 3. The double product further increases it to 6 and finally, the triple product brings the count change ratio to 18. Product development, therefore, can result in enhancement of resolution and, in addition, can produce at least a log-order improvement in the slope of the multiple product response curve. This suggests that our imaging resolution may be improved by utilizing the edge of the response as the sensing element, rather than the peak.

The slope between the last point shown and zero will have an even sharper gradient. This is not known with any degree of accuracy as yet, since the above measurements were taken with a 1 cm scan spacing of the source.

Paralleling this investigation of detector performance with the rack and pinion positioning fixture (approximate accuracy and resettability 1.5 mm), a means was sought for making precise source position measurements on a much finer coordinate grid system. It so happens that an obsolescent commercially-produced organ imaging device (Searle Pho-Dot scanner) incorporated a high-precision, extremely sturdy, motorized detector-positioning system, and modification of such a unit as an automatic positioning fixture appeared possible, if one could be obtained.

Fortuitously, after considerable search, a Pho-Dot unit was located; although inoperative, it could be made available on a loan basis. Upon acquiring the equipment, it underwent substantial repair, and tests were run to ascertain its reliability, repeatability, and tracking accuracy. The outcome indicates that our detector, mounted in the Pho-Dot unit, should be able to sweep a 20 x 20 cm minimum field size with excellent accuracy and precision. Further alterations to the equipment are in the design stage that will permit unattended programmed operation (overnight, for example) so that resolution data, perhaps in increments as small as 1 mm, may be readily obtained.

Also envisioned are facilities providing punched paper tape output for further data reduction on a large computer and curve plotting. Under current development are plans for utilizing the logic in the Pulse Height Analyzer to control the entire data acquisition system. A logic pulse from the PHA

will enable the modified Pho-Dot scanner to reposition the detector at its next X-Y coordinate, and when statistically sufficient counts have been taken, the PHA will produce both a printout of raw counts and a punched tape output. Moreover, arithmetic capabilities of the dedicated Data General computer, associated with the PHA, would produce the K-corrected values as well as multiproduct terms, for printer and punched paper tape output.

4. Objectives for the remainder of this year:

a. Investigation of the interrelationships of the recessed and promontory crystals with respect to optimizing their contributions to the imaging process. Further analyses will be conducted into the multiple product slope vs. displacement characteristics, with the aim of developing algorithms to translate multiple product data into position information.

b. Tests on the 2.5 mm-wide crystal, used as a prototype that will ascertain the extent to which masking of a crystal-PM interface can affect pulse height and thereby shift the spectral peak. This technique can be utilized to produce five separate peaks in the combined spectrum of our proposed detector (refer to Figure 23). Thus, instead of obtaining superimposed spectra from the two end crystals, one of the peaks can be shifted by masking its crystal. This results in separable output, R_1 and R_5 , from these crystals, and the resultant multiproduct information can furnish important left

and right source position information.. To make room in the spectral display for the shifted peak, CsI(Tl) with its reduced pulse height, will be substituted for the CsI(Na) used previously in the first detector. Then, by similarly masking one of the two promontory CsI(Tl) crystals, its display can be shifted below that of the other crystal.

c. Studies to determine whether any significant improvement in the 40% fwhm resolution of the 2.5 mm-wide NaI(Tl) crystal can be achieved with resurfacing and/or a different PM tube. The unit is to be returned to the manufacturer for resurfacing and replacement of its Homamatsu PM with an RCA PM.

d. Determinations of the intrinsic resolution of crystals having widths intermediate between the two dimensions (2.5 and 7.6 mm) already studied. Since there is a possibility that crystal resolution may follow a complex function that improves at some dimension falling between these values, our current detector will be modified by successively reducing one of its 7.6 mm-wide NaI(Tl) crystals, in steps, to 3.5 mm. Subsequent studies will conclusively bracket the optimum crystal dimension vs. resolution factor for this configuration.

e. Completion of prototype Mod II design, and placing an order for its manufacture. This detector will have 3 recessed NaI(Tl) and two CsI(Tl) promontory crystals

as shown in Figure 23. The dimensions of the individual crystals will utilize the results of (a), (b), (c), and (d) above and other appropriate physical guidelines, e.g., field size necessary to view organ or body regions of interest.

f. Completion of the modifications to the Pho-Dot scanner, to allow programmed positioning of the detector element in an X-Y coordinate grid, using increments of 1 or 2 mm over a fixed point source.

g. Modification of pulse-height analyzer to automatically control Pho-Dot scanner, in addition to performing such functions as acquisition of count data at each increment, matrix K-correction, arithmetic operations to obtain selected multiple-region products, and output of data onto punched tape for further computer analysis. These modifications will include the purchase of the necessary hardware (increasing computer memory size, from 8k to 24k, ROM devices for automatic control of gain and zero drift, etc.) and writing programs for interactive control of the entire process.

h. Testing and checking out the modified Pho-Dot transport system and the control programs for the modified pulse-height analyzer. Procedures will be developed to facilitate tests of various system components.

C. Proposal for Second Year

1. Research Plan and Objectives:

a. The automated positioning mechanism and the optimized detector element (Mod II) will be used in gathering multiple-product response data, taking increments of approximately 1 mm. The goal of this experiment will be to evolve the response pattern of an N-element array of detector elements from a single detector element response pattern. This can be described briefly as follows: A single, representative detector, moving along a locus of X and Y coordinates, can fully describe the performance of any multi-element detector array, through the principle of superposition. Thus, the performance parameters of an N-element detector array may be readily synthesized from the response data matrix obtained as the automated positioning system incrementally scans the X-Y field. Each individual element of the multiple detector array "sees" the source in an identical fashion as the single pilot detector element, when it was positioned at that same relative location. Since the detectors' elements are symmetrical, the position directly over the source at the zero starting position may be thought of as the central axis of the array and the response pattern for any size array may be generated through the symmetry of the response pattern around this central position.

Similarly, the response to any number of source positions may be generated by direct summation of the individual responses -- the extreme cases being the response to a single point source at any position under any of the detectors, and alternately, the responses to point sources under all of the N detector elements simultaneously. By selectively removing or adding point source responses it will be possible to generate response patterns analogous to any planar source configuration, i.e., line, curvilinear, circular, etc. In this manner, the response pattern for an N -element array will be generated with the use of a single detector element.

b. Since the response pattern evoked for any shape of source configuration and fixed array position would be a series of multiple product responses for each detector element, detector movement can be simulated by translating the entire pattern to the next coordinate position, iteratively summing the individual source responses as before, at each position to obtain the change of the multiple-product response as a function of array motion.

c. In conjunction with (a) and (b) above, work will begin at this point on the development of algorithms for the reverse of the above operations, i.e., having accumulated a set of product responses and product response derivatives, to take these data and develop the

outlines of the unknown source configurations that generated them.

d. Data from (a) and (b) above will also be used to ascertain the optimum size of a prototype N-element array, (Mod II) configuration.

e. Repeat (a), (b), (c) and (d) above with a new detector (Mod III) configuration described below.

Prototype Detector Element, Mod III: As discussed in the progress report above, the multiple product response (MPR) suggests that the gradient of the count change could be more effectively used for imaging than the peak. Moreover, the MPR spatial response characteristics improved with an increase in the number of recessed crystals and the product peaks yield a resultant peak which crests over the detector element's center. To take advantage of these facts, a new detector element design (Mod III) is proposed and shown in Figure 25 as part of the N-element array that could be developed. The single element is outlined in the upper left hand corner and consists of 9 crystals, R_1 through R_5 , which are recessed, and the associated promontory crystals P_1 through P_4 , shown cross-hatched in the drawing.

The configuration, for purposes of experimentation and testing, consists of 9 crystals. By adding additional crystals, however, the 9-crystal test element becomes only a portion of a larger mosaic of recessed and promontory

crystals. The crystals of the new element are separate entities, each having its own PM, which will substantially facilitate data acquisition and reduction.

By analogy to the previous MPR developed using three recessed crystals, the new design with 5 recessed crystals would allow the following products: $(R_1 \cdot R_2)(R_1 \cdot R_3)(R_1 \cdot R_5)$
 $(R_1 \cdot R_4)(R_2 \cdot R_3)(R_2 \cdot R_4)(R_2 \cdot R_5)(R_3 \cdot R_4)(R_3 \cdot R_5)(R_4 \cdot R_5)$ The resultant response is thus $R_1^4 \cdot R_2^4 \cdot R_3^4 \cdot R_4^4 \cdot R_5^4$ which produces an extremely sharp slope at any position off the central axis or R_3 . The response of this detector element, because of its symmetry, thus provides MPR data for both X and Y axes simultaneously, akin to a surface of revolution that would be obtained by turning the X axis response, as depicted in Figure 23 through 360°.

There are several other unique aspects to the design of this proposed detector element.

- i. In terms of response, the output of the larger mosaic may be envisioned as a series of ordered multiple products where the MPR is as originally discussed, $R_1^4 \cdot R_2^4 \cdot R_3^4 \cdot R_4^4 \cdot R_5^4$ with the various R values being contributed in a programmed, ordered array. For example, MPR could be the 9 crystals outlined in solid black; MPR₂ would then be the 9 crystals outlined in the heavy, dashed, black lines, where R_3 is now seen as R_1 ; MPR₃ is then the 9-crystal response (light dashed lines) beginning at R_5 ; MPR₄ would start at position R_2 ,

etc. In this manner, an MPR matrix would be obtained that is governed by the position in the mosaic of the contributing crystals and their relationship to the source geometry and position.

ii. Having separate crystals, it is now possible to provide a completely variable depth for the recessed crystal, thus allowing selection of response sharpness and multiple-product resolution for widely-varying imaging applications. In addition, this will yield information in terms of $1/r^2$ response, on the Z axis position of the source.

iii. The ability to vary the depth of the recessed crystal also means that recessed and promontory crystal positions may be reversed. Thus, in terms of the output of the mosaic, R_1 now takes the position of P_1 , P_4 becomes R_3 , etc. and a second MPR matrix is obtained, which in effect produces a scan-like motion of the entire mosaic. By again reversing the recessed/promontory configuration, the detector element's spatial response is shifted back to its original center. Crystal movement could thus produce a nod-like, hunting motion that can serve as a vernier in precisely delineating the outline of the object being imaged. The ability to reverse recessed/ promontory crystal geometry for fine scanning emerges as one of the

more promising attributes of this new detector design.

The dimensions of the crystals, 1/2" diam. x 1.5" long, were chosen to enable comparison with the present rectangular configuration.

f. Variable depth of the recessed crystals in the configuration of the present detector would also be possible if PM tubes matching the dimensions of the rectangular crystals were available. This may be possible with the use of parallel-plate electron multipliers. These devices are simple but elegant, consisting of very thin glass plates coated with silicon and aluminum separated by approximately 1 mm. Electron multiplication of the order of 10^5 - 10^6 takes place after one or more electrons enter the aperture and cascade back and forth between the plates. The units may be operated in parallel and can be configured to exactly fit the rectangular face of the present crystals. Because of the flexibility of the parallel plate dimensions, it should be possible to obtain rectangular or square configurations with a range of sizes. These devices are, however, generally used in a vacuum atmosphere without a glass envelope or photosensitive surface in such devices as mass spectrometers, and are presently unavailable with evacuated glass envelopes. This means that considerable design work and experimentation will be necessary before they can be tested with a crystal.

Nevertheless, because of their impressive possibilities, we are eager to fit a prototype with a photocathode. We have contacted Dr. Soren Berg at the Institute of Technology of the University of Uppsala in Sweden, in whose department these devices are made (11,12,13), and he has kindly offered to provide us with some samples (without charge) for experimentation.

g. Experiments similar to (a) and (b) above will be performed to determine the sensitivity of a given size N-element array, notably the minimum detectable levels of lung burdens of the transuranics. A chest phantom of tissue-equivalent material containing a rib cage and cavities filled with mock lung material of appropriate density will be used to test the array. The lung material may contain known amounts of radionuclide, using small point sources grouped in any configuration.

h. We intend to experiment with crystals having a parabolic-shaped front surface, as well as other geometric shapes, in an endeavor to increase light collection, improve spectral resolution, and sharpen the crest of the spatial response curve. Response is broadened (see Figure 13) by the flat face and broad intercept geometry presented by the crystal. Crystal shape may favorably affect the spatial response of both promontory and recessed crystals, and could contribute significantly to the present state of the art.

i. We would like to test a semi-conductor version of the Mod III detector element configuration, replacing the NaI crystals with Si(Li) detectors in the same recessed/promontory geometry. Because PM tubes are not required, the Si(Li) crystals can be made smaller, and a larger number may be placed in a 1.5 x 1.5 in. cryostat. This would allow the ordered MPR matrix as described previously to be developed by a device the size of only one element of the large NaI array. The rationale for this experiment would be the superior spectral resolution of the Si(Li) detectors. Unlike NaI, these devices are capable of resolving the L_{α} , L_{β} , and L_{γ} X-rays of plutonium and the other transuranic elements. In conjunction with the X,Y axis information available via the MPR function, Z axis information could be obtained by the ratio of the counts under the L X-ray peaks. This ratio would change as a function of depth below the skin due to energy absorption. Such a device would have immediate application as a plutonium wound-counter, significantly reducing the amount of exploratory surgery.

D. Significance

The potential importance and the novel contribution of this project resides in the ability to define the spatial position of a source of radiation without the use of a passive, count-rate restrictive collimator, as with imaging devices currently in use.

One of the important applications of this device will be to define, with greater accuracy than presently possible, the location within the body of accidentally-ingested or inhaled radionuclides. This is of consequence in the accurate assessment of dose commitment due to deposition of radioactivity at some specific site, particularly the inhalation of the transuranics, most of which are alpha particle emitters and therefore especially hazardous. Subsequent medical treatment, e.g., lung lavage and/or chelation therapy, may also be dependent on accurate dose estimation.

Another important application of such a device is in nuclear medicine, where organ imaging by uptake of radionuclides is a much-used diagnostic tool. The importance of an improved means of detection, in this case, would be the reduction of radiation dose from levels now necessary for good imaging. Reduction in dose might also justify imaging under circumstances where the current-exposure requirements would leave risk-benefit considerations open to question.

Other potential uses of the detection approach we have developed would include surveillance and monitoring of radioactive plumes and clouds in the atmosphere, as might emanate from nuclear plants or perhaps from weapons testing. A version of the n-element detector could provide data as to shape, size, and activity borne in the air mass, while a network of units would furnish tracking information and dispersion data.

E. Budget for Second Yeara. Salaries and WagesScientific Personnel

Principal Investigator:

Gerard R. Laurer, Ph.D.

Senior Research Scientist (0.75 man-year) N.C.*

Co-Investigators:

Merril Eisenbud, Sc.D.

Director, Laboratory for Environmental
Studies (0.05 man-year) N.C.*

Norman Cohen, Ph.D.

Assistant Director, Laboratory for
Environmental Studies (0.05 man-year) N.C.*

Graduate Research Assistant

George Karron

(1.0 man-year) 14,640

Support PersonnelSecretary, 20% 2,000

Sub-Total \$ 16,640

b. Indirect Costs

Approved rate of 52.5% of salaries and wages

8,736

*Support of these individuals is from National Institutes of Environmental Health Sciences, National Institutes of Health, Grant No. ES 00260.

c. Equipment

In excess of \$1,000:

TN 4000 Computerized Pulse Height
Analyzer System, including:

TN 4000-4K	4096 channel analyzer
with CRT	with CRT
TN 1241	Analog to Digital
	Converter
TA 4016	16 K CPU Memory
TA 4061	Dual Floppy Disk Storage
TN 4100	Flextran Software
TA 1115	Diablo 1620 printer/ keyboard/plotter

\$27,635

9 ea. 1/2" NaI(Tl) crystals @	
\$475	4,275
9 ea. Scintillation preamps	
@ \$120	1,180
9 ea. Pulse amps @ \$275	2,475
1 16 input multiplexor-router	2,950
1 NIM Bin and Power Supply	1,135
1 Dual magnetic tape cassette	4,750
2 ea. High voltage power supplies	
@ \$595	<u>1,190</u>

17,955

d. Supplies and MaterialsRadioactive standard solution for
construction of various source
configurations; glassware,
cassette tape cartridges,
teletype and punched-tape
paper, etc.

1,500

e. Publications

500

f. Travel

1,000

g. Other

Computer time @ \$250/hr for 10 hrs

2,500

Development costs - consultation, materials,
fabrication -- for parallel plate P.M.
configuration

1,500

Fringe benefits: approved rate of 20.5%
of salaries and wages

3,411

Electronic repair services

2,000

TOTAL

\$83,377

F. Facilities Available

1. Tracor-Northern, Model TN 1700, 4096 channel, pulse-height analyzer. This is a computer-based analyzer, using a Data General Nova computer frame. Current memory size of 8K words would be upgraded to 24K and utilized interactively to control data acquisition of PHA.
2. Associated electronic equipment necessary for developing input to analyzer from detector element, viz.,
 - a. Ortec Model 113 scintillation pre-amplifier
 - b. Ortec Model 472 spectroscopy amplifier
 - c. Harshaw Model NV-25 high-voltage supply
 - d. Hamner Nim-Bin Model WH-84 power supply to house and power above modules.
3. Other equipment
 - a. Teletypewriter/paper tape punch
 - b. Tracor-Northern Model TN 1144, X-Y recorder
 - c. Nuclear-Chicago Pho-Dot scanner
 - d. Texas Instruments Model 59 Programmable calculator with PC 100 A printout
 - e. 8' x 8' x 8' whole body counter with 6" steel walls for low level radiation measurements
 - f. Tissue-equivalent chest phantom

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Figure 1

Dual-Crystal Pulse-Shape Discrimination

Dual Crystal Pulse-Shape Discrimination

Figure 2

-- Single Detector Element:
Plan and Elevation Views

Elevation

Plan

Single Detector Element

Figure 3

"Point" Source of Photons Centered Under Detector Element:
Ratios $S_{NaI}(Tl)/S_{CsI}(Tl)$, $S_{NaI}(Tl)/S_{CsI}(Na)$,
 $S_{CsI}(Na)/S_{CsI}(Tl)$ Describe Source Position

Side View

Isotropically radiating
"point" source of photons

Top View

Figure 4

**Photon Source Moved Under Detector Element:
Different Ratios (Figure 3) Describe
New Source Position**

Side View

Isotropically radiating
"point" source

Top View

Figure 5

Detector Elements Arranged in "N" Element Array:
Axes Rotated 90° , Sequentially

"N" Element Array

Figure 6

Characteristics of Various Crystal Materials

(From Harshaw Research Laboratory Report)

Material	Wavelength of Maximum Emission (nm)	Decay Constant (μ s)*	Scintillation Cutoff Wavelength (nm)	Index of Refraction**	Density (g/cc)	Hygroscopic	Scintillation Conversion Efficiency (%)***
NaI(Tl)	410	.23	320	1.85	3.67	Yes	100
CaF ₂ (Eu)	435	.9	405	1.47	3.19	No	50
CsI(Na)	420	.63	300	1.84	4.51	Yes	85
CsI(Tl)	565	1.0	330	1.80	4.51	No	45
⁶ LiI(Eu)	470 ¹	.94	450	1.96	3.49	Yes	35
Plastics ²	350-450	.002-.020 ³	Varies	Varies	1.06 ³	No	5 ³
Liquids ²	350-450	.002-.008 ³	Varies	Varies	0.86 ³	No	5 ³

* Room temperature, best single exponential decay constant, $I_0 e^{-\lambda t}$

** At emission maximum

*** Referred to NaI(Tl) with S-11 photocathode response

¹ Primarily used for neutron detection

² Presented for comparison only, Harshaw does not manufacture

³ Dependent upon composition, values given are typical

Emission spectra of NaI(Tl), CsI(Tl) and CsI(Na) compared to the relative spectral sensitivities of S-11 and bialkali photomultiplier tube types. The emission curves have been normalized to 100% for illustrative purposes. Harshaw Research Laboratory Report.

Figure 7

Prototype Detector Element

NaI (TI)
0.3"×1.5"×1.5"

CsI (TI)
0.3"×0.75"×1.5"

1.25" Dia.×0.5" thick
Quartz light pipe
tapered to 1.5" sq. base

Photomultiplier Tube

Section A-A

Figure 8

CsI(Tl) Output:
88 keV ^{109}Cd (Collimated)

Relative Counts

88 keV, ^{109}Cd - CsI(Tl)

Energy

Figure 9

-- CsI(Tl) + NaI(Tl) Output:
88 keV ^{109}Cd (Collimated)

Figure 10

NaI(Tl) Output:
88 keV ^{109}Cd (Collimated)

Relative Counts

88 keV-NaI(Tl)

Energy

Figure 11

**CsI(Tl)/NaI(Tl) Response to Motion of
Collimated ^{109}Cd Source: Geometric
Configuration as Indicated**

Figure 12

CsI(Tl)/NaI(Tl) Response to Motion of Uncollimated
 ^{109}Cd Source at Several Distances from Detector
Face: Measurement Conditions as Indicated

Source to Crystal (cm)

○ = 5 cm

△ = 10 cm

◇ = 15 cm

■ = 20 cm

Bi Absorber

Source to Crystal Distance

5 cm

10 cm

Source Motion

Q CsI

CsI (cpm)/NaI (cpm) Normalized

Source Position (cm)

Figure 13 —
CsI(Tl) Response
Region 1

Figure 14

Prototype Detector Element Output, Source
Under Center NaI(Tl) Crystal

Figure 15

Spectral Response of 7.6 mm wide x 38 mm long
NaI(Tl), CsI(Tl), CsI(Na) to ^{109}Cd

Spectra Response of 7.5 mm Wide $\times$ 38 mm Long CsI(Tl), CsI(Na) and NaI(Tl) to ^{109}Cd (88 keV)

Figure 16
Spectral Resolution of 2.5 mm wide
NaI(Tl) Crystal

Collimated Source Directed at 2.5 mm Edge of 2.5 mm ×
38 mm × 38 mm, NaI(Tl) Crystal

Figure 17

Response of 2.5 mm wide NaI(Tl) to Collimated
Source Directed at 38 mm x 38 mm Face

Change in Peak Channel vs. Horizontal Position of Collimated Source

Figure 18

Response of 2.5 mm wide NaI(Tl) to Uncollimated
Source Irradiating 38 mm x 38 mm Face

Crystal Response to Uncollimated Source Irradiating 38mm × 38mm Face

Figure 19

Change in Peak Position versus Vertical Position
of Collimated Source

● Change in Peak Channel vs. Vertical Position of Collimated Source

Peak in Ch 92: Collimated Source Interactions
at Center of 38mm Face of Crystal.

Figure 20

Plot of $R_1 \rightarrow R_4$ and Ratios R_2/R_1 and R_3/R_2

Plot of $R_1 \rightarrow R_4$ and Ratios R_2/R_1 and R_3/R_2

Figure 21

Detector Product Terms vs. Displacement

Detector Product Terms vs. Displacement

Figure 22

Multiple Product Response $-(R_1 R_3 \times R_2 R_3)$
versus Source Displacement

Figure 23

Present Detector Element Compared to
Proposed 3-Recessed, 2-Promontory
Detector Element Design

Present Detector

Proposed 3-Recessed, 2-Promontory
Detector Design

Figure 24

Slope of Spatial Response versus Product
Development for 3-Recessed, 2-Promontory
Detector Element (Mod II)

Effect of Product Development on Slope of Spatial Response of Synthesized 2 Premontory, 3 Recessed Detector Array.

Multiple Product Function (MPF)

Displacement (cm)

Figure 25

Proposed Mod III Detector Configuration Detector
Element Consists of 5-Recessed ($R_1 \rightarrow R_5$),
4-Promontory ($P_1 \rightarrow P_4$)

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