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A NEW NEUTRON DOSIMETER AND
NEUTRON-SPECTRUM MODEL FOR
NUCLEAR ACCIDENT DOSIMETRY

AUTHOR:

J. C. Bailey

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE GASEOUS DIFFUSION PLANT

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**UNION
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OAK RIDGE GASEOUS DIFFUSION PLANT
P. O. Box P
Oak Ridge, Tennessee 37830

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Date of Issue: October 2, 1969

Report Number: K-1763

Subject Category: INSTRUMENTS

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FOR NUCLEAR ACCIDENT DOSIMETRY

J. C. Bailey

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Author: J. C. Bailey

A B S T R A C T

The ORGDP nuclear accident dosimeter utilizes bare and cadmium-covered gold for the measurement of thermal neutrons, cadmium-covered gold and boron-shielded copper for the measurement of resonance neutrons, and sulfur and boron-shielded indium for the measurement of fast neutrons. To avoid orientation effects resulting from self-shielding, the gold and copper are in the form of spherical shells.

Interpretation of the measurements is based upon a spectral model comprising a thermal region from 0 to 0.5 ev; a slowing-down region from 0.5 ev upward, in which the fluence per unit logarithm of energy is a linear function of $\log E$, but weighted by the fraction of neutrons originating in the fission spectrum at energies higher than E ; and a fast region having the shape of a fission spectrum but with energies which may be shifted from those of the fission spectrum by a constant factor. The copper and gold measurements are considered to define the entire slowing-down spectrum, and the shift of the fast portion of the spectrum is determined from the indium-to-sulfur response ratio after these respective values have been corrected for the contribution of the slowing-down spectrum.

This dosimetry scheme was tested experimentally with 4 different neutron spectra. The dosimeter yielded first-collision tissue doses in air which agreed with absolute proportional counter determinations to $\pm 10\%$. Doses to phantoms determined from the spectral data of the dosimeter and the activation of saline solution in the phantoms agreed with proportional counter values to within $\pm 13\%$. Comparisons of experimental responses of plutonium, neptunium, and uranium fission foils of the Hurst threshold detector unit with responses which would be expected on the basis of the spectral interpretation described above showed a bias of 15% between the two methods. With correction for this bias, the comparisons were within 15% in all cases. To permit these comparisons, a 100-group neutron transport code for the IBM-7090 computer was used to calculate effective cross sections for the fission foils when they are shielded by 1.65 grams of ^{10}B per square centimeter, as in the Hurst unit. The results of these calculations are given.

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A NEW NEUTRON DOSIMETER AND NEUTRON-SPECTRUM MODEL
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Introduction

The dosimeter described in this report was developed to meet the need for a low-cost nuclear accident neutron dosimeter which would fulfil the same functions as the relatively expensive Hurst threshold detector unit.^{1,2*} In 1959, Hurst units were installed at preselected locations in some plants of the Atomic Energy Commission to permit evaluation of neutron spectra at these locations in the event of an accidental critical reaction. The objective was to provide emergency monitoring capabilities in areas of major importance with respect to possible criticality accidents. Although the Hurst threshold detector unit was considered to be the best available device for monitoring such accidents, a number of problems in its use were recognized,³ particularly in its application to the monitoring of large production areas. These problems involved the high cost (over \$1000 per unit), the low sensitivity of the uranium, neptunium, and plutonium fission-foil neutron detectors, and the rapid decay of the fission-product activities by which neutron data are obtained from these foils. In addition, only an estimate of the fluence in the broad resonance-energy band from thermal energy to the effective threshold of plutonium at 14 kev can be obtained from the detectors used.

Development of the dosimeter described in this report was undertaken to provide a device with greater sensitivity, longer lived activities, and much lower cost than the Hurst threshold detector unit, and which would compare favorably with the Hurst unit with respect to accuracy of dose measurements. In particular, a cost target of \$50 per complete unit was adopted so as to achieve a dosimeter of sufficiently low cost that total coverage of large production areas with the units would be economically feasible.

Both the present dosimeter and the Hurst threshold detector unit comprise neutron detecting materials which are activated by neutrons in different energy regions. They may be installed in locations where potentialities for criticality exist, and in event of an accident the detectors would be retrieved, the induced activities measured, and from these the energy distribution of the neutrons for that particular location would be determined. The concentration of radioactive sodium-24 in the blood of persons exposed to radiation from the critical reaction would also be measured. On the basis of the neutron-spectrum data obtained from a dosimeter which was near an irradiated individual the sodium activity would then be interpreted in terms of dose to the individual.

*References are given at the end of the report.

Differences between the two devices involve not only the choices of neutron detecting materials but also the methods of handling data obtained from them. The responses of the threshold detectors of the Hurst unit are utilized to develop a histogram representation of the spectrum, each group of which can be weighted by appropriate factors for necessary calculations. In order to cover the important neutron energy range from 14 kev to 0.75 Mev, for which there are no known nuclear reactions which lend themselves to direct use as detectors, the Hurst unit utilizes a plutonium fission foil which is enclosed in a shield of isotopically enriched boron-10 to achieve, in effect, a threshold type response. This shield represents an appreciable part of the cost of the Hurst unit. With the new dosimeter, the neutron measurements are interpreted in terms of a spectral model, the necessary parameters of which are determined from the responses of a minimum number of detectors. Thus, for regions not measured directly, neutron fluence values may be calculated on the basis of this model.

Dosimeter

The components of the new dosimeter, designated as the ORGDP dosimeter, are shown in figures 1 and 2. Figure 3 shows the elements assembled and supported in a 0.001-inch-thick polyethylene bag to form the complete dosimeter. The neutron detectors consist of a sulfur disc,^{4,5} an indium sphere, 2 hemispherical copper shells, and 2 spherical gold shells. The copper and indium are enclosed in hemispherical shields composed of boron (not isotopically enriched) and Teflon, and one of the gold shells is enclosed in a cadmium shield. Used in conjunction with the neutron dosimeter is a gamma dosimeter consisting of 2 photoluminescent phosphate-glass rods contained in a capsule of lithium fluoride, the lithium being enriched in the lithium-6 isotope, to provide neutron shielding for the gamma detectors.⁶ Specifications for the various elements of the neutron dosimeter are given in table 1.

Both the cadmium-covered gold and copper are resonance neutron detectors, with major resonances at 4.9 ev and 580 ev, respectively. The purpose of the boron around the copper is to reduce the activation of copper by neutrons in the thermal energy region and in the low energy portion of the resonance region, thus enhancing the selectivity of the copper for neutrons at its first resonance energy. The copper and gold were fabricated into spherical-shell form to eliminate directional effects, since self-protection is very important for resonance detectors and flat foils are not isotropic in their response.

Indium and sulfur are fast neutron detectors, the reactions of interest being $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ and $^{32}\text{S}(n,p)^{32}\text{P}$, respectively. The indium is shielded with boron to reduce interfering activities which are induced in indium by neutron capture.

Cost estimates indicate that the dosimeter could be produced in quantities of 1000 or more at a cost very close to the target price of \$50 per complete unit.

Counting Methods

The copper, gold, and indium spherical elements are all counted in a well-type scintillation gamma counter. A plastic (methyl methacrylate) container with 1/8-inch-thick walls is used inside the counter well to provide beta shielding and to absorb the positron emission from copper-64 so as to maintain a uniform counting geometry for the positron annihilation gamma rays by which the copper activity is measured. The counters were calibrated for ^{198}Au with an evaporated standardized ^{198}Au solution, and for ^{64}Cu by comparing the count rates of thin gold and copper foils exposed simultaneously to thermal neutrons in the deuterium-oxide thermal tank at the ORNL Bulk Shielding Reactor.

Because of the many factors which affect the response of thick-foil resonance detectors, the calibrations obtained in this way for thin foils and residues are not directly applicable to the relatively large thicknesses of the spherical detectors of the dosimeter, but these "thin-foil" calibrations provide a means for comparing counters of similar construction. In addition, the absolute calibration for gold in thin foil form was used in monitoring the neutron exposure of dosimeter elements in the experiment described below, which experiment yielded an empirical calibration of these elements.

Calibration of the gold and copper dosimeter elements themselves was carried out by means of a 2 1/2-inch-diameter beam of neutrons from the Brookhaven Graphite Reactor, where the beam was brought outside the reactor into a concrete-shielded enclosure. It was anticipated that the neutrons in this beam would closely approximate the classical $1/E$ spectrum⁷ in the resonance region, and this was verified by a measurement of the resonance activation integral of copper-63 in thin foil form. The integral as determined in this beam by the cadmium-ratio method was lower by less than 2% than that measured by Dahlberg, Jirlow, and Johansson⁸ under conditions where the energy distribution of the beam was determined directly by means of a fast chopper and where corrections were made for deviation of the beam from $1/E$ dependence. A note on the determination of the resonance activation integral is given in appendix 1.

For calibration of the dosimeter elements, the absolute magnitude of the flux in the resonance-energy region of the beam at Brookhaven was measured with very thin cadmium-covered gold foils. The count rates on copper and gold spheres exposed to this known beam then gave a direct calibration of these detectors.

The indium spheres were calibrated by comparing the $^{115\text{m}}\text{In}$ activity induced in the spheres with that induced in 0.020-inch-thick indium foils when both types of elements were exposed to a burst of neutrons from the Health Physics Research Reactor at the DOSAR facility of the Oak Ridge National Laboratory. For this comparison, the activities of the spheres were measured with the well scintillation counter and the foils were measured with a sodium-iodide-crystal gamma spectrometer. Fluence values were determined from the foil activities on the basis of $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ cross section determinations carried out at Chalk River,⁹

the cross sections used being shown in figure 4. The cross sections given are based on a gamma yield of 46.0 photons (0.335 Mev) per 100 disintegrations. It is emphasized that these values were considered to be preliminary in that some small corrections, possibly amounting to 2 or 3%, were still to be applied to the measurements. However, they were used in preference to the more widely used values of Martin, Diven, and Taschek^{10,11} because they cover the entire energy range of interest and are supported by the experiments of Cohen¹² and of Heertje, Nagel, and Aten¹³.

Calibration factors, data on counter discriminator settings used, and geometry factors relative to counter calibration are listed in table 2. The primary calibrations given here for the spherical copper and gold detectors may be related to other counters of the same type on the basis of geometries for copper and gold in thin foil form or as residue from dried standardized solutions. The barium-133 geometry serves as a convenient reference for comparisons between counters with respect to the indium-115m determination. This barium isotope has a very convenient 10.7 year half life, decays solely by electron capture, and emits 2 closely spaced gamma rays of 0.292 and 0.360 Mev energy, with relative abundances such that the average energy is very close to the 0.335 Mev gamma of indium-115m.

Although useful information could be obtained from the dosimeters within a few hours of exposure, accurate determinations require a longer delay in counting to let interfering activities in the detectors decay. Guides for appropriate counting delays are listed for the various elements in table 3 along with the major interfering activities.

In the case of indium, there are two principal interfering activities--^{113m}In, resulting from inelastic neutron scattering with the 4.28% abundance ¹¹³In isotope, and ^{116m}In, produced through neutron capture by ¹¹⁵In. In addition, the 50-day half-life ^{114m}In resulting from the ¹¹³In(n, γ)^{114m}In reaction may need to be taken into account if counting is delayed for 24 hours or longer. Measurements made at Chalk River⁹ at a few selected neutron energies have shown that the ¹¹³In(n,n')^{113m}In cross section bears an essentially constant ratio of 0.86 to the corresponding ^{115m}In reaction cross section. On the basis of this ratio, the ^{113m}In activity would be about 2% of the ^{115m}In activity after the 6 1/2-hour interval indicated in table 3 for this detector. However, the 54-minute ^{116m}In activity is still appreciable. In order to correct for this, each indium detector was counted two or more times with a period between first and final count of at least 2 hours. A data fitting code¹⁴ for the IBM-7090 computer was then used to calculate the separate 54-minute (^{116m}In) and 4.5-hour (^{115m}In) activities from these multiple counts.

In addition, some samples were counted after delays of 20 hours or more, when the 54-minute ^{116m}In activity would have decayed to negligible levels, and these counts were used as a check on the values computed from the earlier multiple counts. Use of the counter as a single-channel analyzer to obtain a differential count covering the gamma energy range

from 0.24 Mev to 0.52 Mev was found to reduce the count rate of ^{116m}In by a factor of 3.2 as compared to that obtained when an integral count of all energies greater than 0.24 Mev was obtained. This does not change the ^{115m}In count rate. Thus, use of the differential counting mode rather than integral counting reduces by about 2 hours the time required for the ^{116m}In count rate to decay to any given fraction of the ^{115m}In count rate. The differential counting mode also discriminates against the long-lived ^{114m}In isotope. In these tests the differential counting results indicated that the count rate for this isotope was less than 1% of the ^{115m}In count rate for the first 24 hours after exposure.

Spectral Model

Data obtained from the detectors of the dosimeter are interpreted in terms of a spectral model, pertinent parts of which are illustrated in figure 5. Here the fluence per unit logarithm of energy is represented on a linear scale and the energy on a logarithmic scale; thus, the number of neutrons in any energy region is proportional to the area under the curve for that region. The total spectrum is considered to comprise a thermal energy region, a slowing-down spectrum, and a fast spectrum.

Thermal Spectrum. The thermal neutron fluence is determined from the cadmium difference method with the gold detectors in the usual way. The thermal region is not represented on the graph and is not considered further.

Slowing-Down Spectrum. In the region below fission energies the slowing-down spectrum is considered to be represented by a straight line function on the type of graph shown in figure 5. In the region of fission energies this same linear function is weighted by the fraction of neutrons originating in the fission spectrum above the energy in question. This weighting is based on the concept that the number of neutrons slowing down past a particular energy, and hence the fluence per unit logarithm of energy at that energy value, depends upon the number of neutrons originating at all energies above the one in question. As an example, only 21% of the neutrons originate in the fission spectrum at energies above 3 Mev, so at this energy the fluence in the slowing-down spectrum is considered to be 21% of the value which would be indicated by the extended straight line function. The mathematical expression for the slowing-down spectrum is:

$$\phi(\ln E) = (\phi_0 + k \ln E) F, \quad (\text{Eq. 1})$$

where ϕ_0 = fluence per unit $\ln E$ at 1 ev,

k = constant = $\Delta\phi(\ln E)/\Delta\ln E$,

F = fraction of neutrons originating in the fission spectrum at energies greater than E .

As a convenience in converting $\phi(E)$, fluence per unit energy, to $\phi(\ln E)$, fluence per unit $\ln E$, it is noted that $\phi(\ln E) = E \phi(E)$. It is also noted that in the special case where the energy distribution is $1/E$, the fluence per unit logarithm of energy is constant and the graph is a horizontal line.

In evaluating a spectrum from experimental measurements, the activity of the cadmium-covered gold shell is considered to be proportional to the fluence per unit $\ln$ energy at the major gold resonance of 4.9 ev, and the copper activity is considered to be proportional to the fluence per unit $\ln$ energy at the first copper resonance of 580 ev. Thus, these two measurements define the entire slowing-down spectrum.

Fast Spectrum. The fast spectrum, which overlaps the slowing-down spectrum, is considered to have the shape of the fission spectrum, but may be shifted to lower or higher energies. That is, it is a fission spectrum with the energies shifted uniformly by some constant factor. The amount of this shift is determined from the ratio of the fluences indicated by the indium and sulfur after these have been corrected for the effects of the slowing-down part of the total spectrum. The procedure is to first interpret the activities of the indium and sulfur as if they were being used as simple threshold detectors. From the fluence values indicated by each of these detectors is then subtracted that part of the response which would be associated with the slowing-down spectrum as determined from the copper and gold measurements. The ratio of the remaining indium and sulfur fluence values serves as an index to indicate the shift of the fast portion of the spectrum.

Numerical Methods

The responses of the indium and sulfur threshold detectors are evaluated by relating the apparent fluence values--obtained from a simple threshold-type evaluation of the induced activities--to responses which may be calculated more rigorously by numerical integration over selected spectra using the actual cross section curves of the detectors. In addition, the determination of dose at the position of the dosimeter and evaluation of sodium activation in body fluids involves numerical integration, over the entire spectrum, of both the applicable dose curve and the curve for neutron capture in the body (or in a phantom). To facilitate the calculations, the necessary relationships were developed by numerical integrations, carried out for both the slowing-down and fast spectra, and these relationships are shown graphically in figures 7 through 18. The various numerical integrations are described and uses of the graphs are illustrated in appendix 2.

Supplementary Calculations

In the experimental evaluation of the new dosimeter, described below, it was desired to compare fluence measurements obtained with the Hurst

threshold detector unit with corresponding values which could be calculated from measurements made with the new dosimeter on the basis of the spectral model just described. In order to permit this, it was necessary to have accurate cross section values for the fission foils of the Hurst unit. As far as could be determined, however, there were no existing evaluations of the effects of the boron shield on the responses of the fission foils which accounted fully for neutron scattering effects. In an effort to obtain more accurate cross section values which would be applicable to the fission foils when shielded by the boron shield, new calculations were carried out using the IBM-7090 computer and a 100-group neutron transport code.¹⁵ The results of these calculations are shown in figure 6, and the numerical values are given in table 4.

Effective threshold and cross section values, as applied to the threshold detector concept, were calculated from the curves for indium, uranium, neptunium, and plutonium as shown in the graphs of this report, and for sulfur from the data of BNL-325¹¹. These values, relating to a Watt fission spectrum, are listed in table 5. Listed for comparison are the ORNL cross sections for the fission foils of the Hurst threshold detector unit as determined experimentally by Johnson, et. al.¹⁶. In the report of this experimental calibration of the fission foils, effective cross sections weighted to a Godiva fission spectrum are listed and it is noted that correction factors are applied to correct for the effects of the boron shield. For direct comparison, cross sections corresponding to those for boron-shielded foils are also listed.

In the interpretation of the fission foil measurements, fluence values were first determined on the basis of the experimental calibration of the fission-foil counters¹⁶, and these values were then corrected to correspond to the new effective cross sections shown in table 5.

A precise designation of an effective threshold for plutonium is somewhat questionable, since such a value is necessarily based on the assumed distribution of neutrons in the slowing-down energy region. Given an assumed spectrum, however, such a threshold energy can be calculated. On the basis of an assumed $1/E$ spectrum which decreases in the fission-energy region as described in this report, the effective threshold of plutonium corresponding to an effective cross section of 1.75 barns was calculated to be 14 kev.

Experimental Evaluation

In order to test the application of this dosimetry scheme, groups of the new dosimeters were exposed to radiation from the Health Physics Research Reactor under four different configurations designed to produce appreciable changes in the neutron spectrum. The arrangements included exposure directly to radiation from the reactor, through a 30-cm-thick polyethylene shield, and through 12.7 cm of iron. In addition, one exposure was made with the iron shield behind the detectors from the reactor to add a component of scattered radiation. Included in the tests were Bomab polyethylene phantoms filled with saline solution and Hurst threshold

detector units. The dose was measured with a Hurst absolute proportional counter under steady state operation of the reactor under the same configurations, and these measurements were related to the bursts of the tests on the basis of sulfur detectors placed near the reactor in each case.

All of the dosimeter exposures were 3 meters from the reactor and 1.5 meters above floor level, which was also the height of the reactor. The polyethylene shield measured 1.5 meter $\times$ 1.5 meter and was comprised of 27.3 cm polyethylene and 5.1 cm of plywood, and was termed a nominal 30-cm-thick polyethylene shield. It was interposed between the dosimeters and the reactor with the front face 1 meter from the reactor. The iron shield consisted of 3 panels, each being 91.4 cm wide, 213 cm high, and 12.7 cm thick. These were set on an arc 2 meters from the reactor. The dosimeters were behind one of the side panels and the phantom was behind the opposite side panel to achieve a symmetrical arrangement to expose the dosimeters and the phantom to the same radiation field. Similarly, when the shields were behind the dosimeters from the reactor they were placed 4 meters from the reactor; the dosimeters were exposed in front of one of the side panels and the phantom in front of the other side panel.

The tests in air and behind the polyethylene shield were carried out as a part of some dosimeter intercomparison studies, and for this purpose the distance of the phantom from the reactor was different from that of the dosimeters. In the air burst it was approximately 4 meters from the reactor, and in the exposure with the polyethylene shield the phantom was placed behind the dosimeter units from the reactor with the front surface 4 meters from the reactor. All of the proportional counter measurements were made 3 meters from the reactor, and these were normalized to the position of the phantom on the basis of dose measurements made with Hurst threshold detector units exposed at both distances.

The experimental measurements of these tests are given in table 6, and derived spectral parameters and dose values are given in table 7.

The agreement between the different determinations is indicated in table 8. The dose in air calculated from the dosimeter measurements on the basis of the spectral model and the first-collision dose curve of NBS Handbook 63 agreed with the proportional counter determination to within 10%. The corresponding dose at the position of the phantom, as determined from sodium activity in the phantom solution, agreed with the proportional counter determination to within 13%.

In an effort to check the spectral representation in a somewhat more detailed manner, the responses of the plutonium, neptunium, and uranium-238 fission foils of the Hurst unit which would be predicted from measurements made with the new dosimeter were calculated, and these were compared with the experimental fission foil responses. Of the measurements obtained with the new dosimeter, the most important with respect to these calculations were the indium fluence indications. Indium exhibits a higher response to neutrons just below the nominal 1.5 Mev effective threshold

energy than does uranium, but less response to the lower energy neutrons than either neptunium or plutonium. All of the fission foil values calculated from the ORGDP dosimeter measurements were higher than those determined by direct measurement with fission foils. Differences were 1 to 29%, the average being 15%. Since this was the case for all of the fission foils, these deviations were considered to indicate a bias between the fluence values determined by the two methods, rather than failure of the spectral model. If corrections are applied for a 15% bias of this nature, the calculated and experimental values agree to within 15% in all cases. Further, the doses calculated from the experimental fission foil fluence values with the dose weighting factors recommended by ORNL¹⁶ were also in good agreement with the measurements of the proportional counter, the errors being less than 10% in all cases. It was thus apparent that, as far as dose computations were concerned, the differences in fluence values determined by the two methods were largely counter-balanced by differences in the dose weighting methods used.

In table 9 are listed values derived from measurements with the new dosimeter which indicate the range of spectral variation which was achieved in these tests. The dose per unit sodium activity in the phantom solution varied from 2.38 to 4.12 rad/dis/sec/ml. This represents variation by a factor of 1.7. The fraction of sodium activity in the phantom solution due to slowing-down neutrons varied from 35% to 67%, and the fraction of dose due to these slowing-down neutrons varied from 13% to 41%. The indium to sulfur fluence ratio as derived for the fast spectrum varied from 2.93 to 5.09, representing shifts from fission spectrum energies by factors of 0.83 and 0.58, respectively. These values demonstrated that appreciable spectral variations were achieved.

In view of the demonstrated spectral variations, the close agreements between a variety of independent measurements and corresponding values derived from measurements with the new dosimeter indicated that the data which could be derived from this dosimeter were sufficiently accurate to be useful in evaluating personnel radiation doses in event of a nuclear accident.

Sensitivity

As an indication of the sensitivities of the various detectors, count rates are tabulated in table 10 for a 1-rad exposure to a spectrum like that behind the 12.7-cm-thick iron shield. Also listed are the background count rates and the resulting limits of error (95% confidence interval) for the net count rates, assuming all counts--sample and background--were for 5 minutes. The variations in final dose calculations which would result from errors of the magnitudes listed were also calculated and are listed in table 10. The 95% confidence limits for the dose calculations were then calculated as the square root of the sum of the squares of the individual errors and were found to be 21% for the dose measured in air and 8.6% for the dose determined for a phantom on the basis of sodium-24 analysis. This indicates that in this spectrum a dosimeter exposed to 1 rad would permit sodium activity to be evaluated in terms of dose to

within $\pm 10\%$ with 5-minute counting times for all elements: this limit applies only to statistical variations associated with the counting of the dosimeter elements. Obviously the statistical uncertainties could be reduced with longer counting periods.

Phantom Dose Based on Hurst Threshold Detector Unit Measurements

Neutron doses to the phantoms were evaluated on the basis of the Hurst threshold detector measurements and the activation of the solutions in the phantoms as described in the report ORNL-2748, Part A², but with the more recent dose weighting factors developed at ORNL¹⁶. The equation used for these evaluations was:

$$\text{Dose to phantom} = 9.5 \times 10^8 K \frac{\text{Dose to Dosimeter}}{0.5 \phi(\text{Pu}) + 0.18 \phi_{\text{Th}}}, \quad (\text{Eq. 2})$$

where K is the sodium activity in disintegrations per second (corrected to time of exposure) per cm^3 of blood serum, the factor 9.5×10^8 being applicable to a sodium concentration in serum of 3.2 mg/cm^3 . The factors 0.5 and 0.18 are the average probabilities of neutron capture in the phantom for neutrons in the plutonium response region and the thermal region, respectively, and $\phi(\text{Pu})$ and ϕ_{Th} are the fluences in these respective regions. The denominator in this expression thus represents the neutron capture integral over these two energy regions.

The doses calculated with this expression were greater than those indicated for the phantoms by the proportional counter measurements by from 8% for the exposure directly to the reactor radiation to 61% for exposure behind the 12.7-cm-thick iron shield. The overestimates of dose, which were most pronounced under conditions involving shielding and scattering, were attributed primarily to the relatively high neutron fluences in the resonance region associated with these exposure conditions. Neutrons in this energy region are not measured by the foils used in the Hurst unit and, as noted from the formula, are not reflected in the evaluation of sodium activation in phantom solutions. Because of their low energy, neutrons in the resonance region may contribute little to the dose, so omitting their contribution may not affect the direct dose measurements appreciably. At the same time, however, they may contribute heavily to activation of the sodium in the phantom solutions, and if this activation is attributed to the faster neutrons detected by the foils of the Hurst unit the dose estimates based on solution activation measurements will tend to be too high.

An indication of the effects of resonance neutrons below the plutonium threshold was obtained by evaluating the capture integral, $\int \epsilon(E) \phi(E) dE$, over the range from the cadmium cut-off energy at 0.5 eV to the plutonium threshold at 14 keV, and adding this as an additional term to the denominator of equation 2. Here $\epsilon(E)$ is the probability that neutrons of energy E will be captured in the phantom, and $\phi(E)$ is the fluence per unit energy at energy E. Evaluations of this integral for the various cases were based on the spectral model and on the copper and gold measurements

of the new dosimeter. With these corrections, the phantom doses differed from the proportional counter measurements by from -8% to +24%, which represents an appreciable improvement in accuracy.

Summary and Conclusions

An inexpensive nuclear accident dosimeter, which utilizes only five neutron detecting elements, was developed; two of the elements yield measurements in the fast portion of the spectrum, two in the resonance region, and one in the thermal region. Measurements obtained with these elements are interpreted on the basis of a spectral model comprising three parts--a thermal region, a slowing-down spectrum, and a fast spectrum. In experiments carried out to evaluate this dosimetry scheme, appreciable neutron spectral variations were achieved among four different irradiation arrangements. Values determined from the dosimeter on the basis of the model spectrum and from measurements of sodium activation in the saline solution of phantoms were compared with proportional counter measurements and with measurements obtained with Hurst threshold detector units. These comparisons showed that the dosimetry scheme permitted the major variations in spectra to be identified and evaluated quantitatively from the small number of elements in the dosimeter. Taking the proportional counter measurements as a basis of comparison, the accuracy of the dosimeter for determining the first-collision tissue dose at a point in air was $\pm 10\%$, and the accuracy with which the activity of the saline solution in phantoms could be evaluated in terms of first-collision dose to the phantoms was $\pm 13\%$.

TABLE 1
DOSIMETER PARTS

<u>Part</u>	<u>Description</u>
1. Sulfur Detector	Cast sulfur disc; 3.8-cm (1.5-inch) diameter, approximately 1-cm (0.4-inch) thick, 22 ± 0.05 g. For reproducible results with the burning technique for low-dose measurements ^{2,5} the sulfur is highly purified prior to casting ⁴ and yields less than 1 part per million as residue on burning.
2. Indium Detector	Solid sphere; 10.000 ± 0.005 g, 1.38-cm diameter.
3. Gold Detector	Spherical shells; 0.973-cm outside diameter, 0.010-cm wall thickness (3/8-inch inside diameter, 0.004-inch wall). Weight 0.57 ± 0.02 g per sphere.
4. Copper Detector	Hemispherical shells mounted to form complete sphere; 2.54-cm outside diameter, 0.0254-cm (0.010-inch) wall thickness. Weight 4.6 ± 0.2 g per spherical shell.
5. Cadmium Shield	Hemispherical shells which fit around one gold shell; 1.12-cm (0.440-inch) outside diameter, 0.0648-cm (0.0257 ± 0.001 -inch) wall thickness.
6. Large Boron Shield	Hemispherical shells; outside diameter 3.70 cm (1.46 inch), wall thickness 0.55 cm; 0.49 g natural boron/cm ² with Teflon (TFE) binder of 0.24 g/cm ² ; total density of wall material is 1.40 g/cm ³ .
7. Small Boron Shield	Hemispherical shells; outside diameter 2.46 cm (0.97 inch), wall thickness 0.54 cm; 0.52 g natural boron/cm ² with Teflon (TFE) binder of 0.25 g/cm ² ; total density of wall material is 1.51 g/cm ³ .

TABLE 2
COUNTER CALIBRATION DATA

Detector	Calibration Constant	Measurement	Calibration Isotope	Thin-Foil Counter Geometry	Lower Discriminator (Gamma Energy)	Discriminator Settings, Volts	Count
Cd Difference-Bare and Cadmium-Covered Gold	$7.01 \times 10^4 \frac{n/cm^2}{\text{count/min/g}}^{(1)}$	Thermal fluence	^{198}Au	0.323 ⁽²⁾	0.32 Mev	33.0	16.0
Cd-Covered Gold	$2.60 \times 10^4 \frac{n/cm^2/\ln E^{(1)}}{\text{count/min/g}}$	Resonance fluence per unit logarithmic increment (base e) at 4.9 ev	^{198}Au	0.323 ⁽²⁾	0.32 Mev	33.0	16.0
Copper	$1.43 \times 10^6 \frac{n/cm^2/\ln E^{(1)}}{\text{count/min/g}}$	Resonance fluence per unit logarithmic increment at 580 ev	^{64}Cu	0.0855 ⁽²⁾	0.40 Mev	33.0	20.0
115m Indium	$1.66 \times 10^5 \frac{n/cm^2}{\text{count/min/10 g}}^{(1)}$	Apparent fluence > 1.5 Mev	^{133}Ba	0.489 ⁽³⁾	0.24 Mev ⁽⁴⁾	16.5	6.0
Sulfur Disc	$0.995 \times 10^7 \frac{n/cm^2}{\text{count/min/disc}}$	Apparent fluence > 2.9 Mev	^{32}P	0.627 ⁽⁵⁾			
Sulfur Burned	$1.02 \times 10^7 \frac{n/cm^2}{\text{count/min/g}}$	Apparent fluence > 2.9 Mev	^{32}P	0.627			

(1) Applies to count rates corrected to time of exposure, as determined with a well-type sodium iodide scintillation counter, 3-1/2-inch-diameter x 3-1/2-inch-long crystal, with a well 1-11/16-inch diameter x 2-9/16-inch deep.

(2) Count rate/disintegration rate.

(3) Ratio of count rate to total emission rate of 0.292- and 0.360-Mev gamma rays as measured by a gamma spectrometer.

(4) For differential counting the window width was 7.0 volts, or 0.28 Mev.

(5) ^{32}P in sulfur burning dish with lead back-scatterer.

TABLE 3

PRINCIPAL INTERFERING ACTIVITIES

Detection Reaction			Interfering Reactions			Nominal ¹ Counting Delay	Notes
Reaction	Half-life	Radiation	Reaction	Half-life	Radiation		
$^{32}\text{S}(n,p)^{32}\text{P}$	14.2 d	1.707 Mev β	$^{34}\text{S}(n,\alpha)^{31}\text{Si}$	155 min	1.48 Mev β	10 hr	2
$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$	4.5 hr	0.335 Mev γ	{ $^{113}\text{In}(n,n')^{113\text{m}}\text{In}$ $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$	104 min	0.392 Mev γ	6.6 hr	3
$^{63}\text{Cu}(n,\gamma)^{64}\text{Cu}$	12.8 hr	0.5 Mev γ (Annihilation)		54 min	Multiple γ	12.5 hr	
			$^{65}\text{Cu}(n,\gamma)^{66}\text{Cu}$	5.1 min	1 Mev γ	50 min	

1. Approximate time for the count rates of the short-lived interfering isotopes to decay to less than 2% of the count rates of the isotopes of interest.
2. See reference 5 for a listing of long-lived activities which may be significant with long delays in counting (2 weeks or more).
3. The activity of $^{116\text{m}}\text{In}$ resulting from neutron capture relative to that of $^{115\text{m}}\text{In}$ resulting from fast neutron interactions is highly dependent on the actual spectrum involved³. The value 12.5 hours was based on experimental differential counting results for detectors exposed behind a 30-cm-thick polyethylene shield, which represented the highest resonance-to-fast neutron fluence ratio found in these experiments.

TABLE 4

EFFECTIVE CROSS SECTIONS OF BORON-SHIELDED FISSION FOILS
(1.65 g $^{10}\text{B}/\text{cm}^2$ as B_4C)

Group	Middle of Energy Group	Effective Cross Section, barns		
		^{238}U	^{237}Np	^{239}Pu
1	14.208 Mev	1.118	2.383	2.527
3	11.633	0.9743	2.311	2.359
5	9.524	0.9797	2.183	2.321
7	7.798	0.9429	1.978	2.191
9	6.384	0.7002	1.683	1.191
11	5.227	0.5495	1.362	1.778
13	4.279	0.5370	1.437	1.811
15	3.504	0.5352	1.547	1.887
17	2.869	0.5160	1.574	1.889
19	2.349	0.4943	1.607	1.899
21	1.923	0.4245	1.579	1.858
23	1.574	0.1508	1.572	1.855
25	1.289	0.02801	1.521	1.834
27	1.055	0.01055	1.415	1.746
29	0.8640	0.00202	1.148	1.638
31	0.7074	0.0000	0.7826	1.571
33	0.5792		0.4817	1.520
35	0.4742		0.2579	1.490
37	0.3882		0.1100	1.462
39	0.3179		0.04601	1.433
41	0.2602		0.02308	1.394
43	0.2131 Mev		0.01238	1.359
45	0.1744		0.00721	1.328
47	0.1428		0.00422	1.297
49	0.1169		0.0000	1.276
53	46.67 Kev			1.232
57	17.17			1.165
61	6.316			0.7122
65	2.324			0.4751
69	854.8 ev			0.2455
73	314.5			0.07854

TABLE 5
EFFECTIVE CROSS SECTIONS

<u>Detector</u>	<u>Mean Cross Section for Fission Spectrum</u>	<u>Effective Threshold Energy</u>	<u>Effective Cross Section (Fis. Spect.)</u>	<u>ORNL Cross* Section Values</u>	
				<u>Bare Foil</u>	<u>Boron Shielded</u>
Sulfur	0.0669 b	2.9 Mev (2.5 Mev)	0.297 b (0.229 b)		
Indium	0.175 b	1.5 Mev	0.329 b		
Uranium	0.256 b	1.5 Mev	0.481 b	0.54 b	0.49 b
Neptunium	1.23 b	0.75 Mev	1.57 b	1.60 b	1.39 b
Plutonium	1.75 b	14 kev	1.75 b	1.80 b	1.80 b

*Weighted to a Godiva spectrum of fission neutrons.

TABLE 6
EXPERIMENTAL MEASUREMENTS

Exposure	Fissions	Fluence Values, 10^{10} n/cm ²								Phantom Sodium Activity dis/sec/ml*	Proportional Counter Dose Measurements	
		Thermal	ϕ (Au)	ϕ (Cu)	ϕ (In)	ϕ (S)	ϕ (Pu)	ϕ (Np)	ϕ (U)		Dosimeter Position	Phantom Position
Air	9.09×10^{16}	0.642	0.191	0.521	6.29	2.10	15.3	9.88	4.94	53.3	376	219
Behind Polyethylene	6.60×10^{16}	0.404	0.0719	0.124	0.337	0.0930	1.22	0.609	0.239	8.64	27.7	21.0
Behind Iron	5.36×10^{16}	0.271	0.081	0.216	0.916	0.187	3.82	2.02	0.587	32.4	77.1	77.1
Front Iron	6.85×10^{16}	0.648	0.186	0.497	5.01	1.49	11.2	7.72	3.38	89.3	298	298

* Corresponding to $3.2 \text{ mg }^{23}\text{Na/cm}^3$.

TABLE 7
DERIVED SPECTRAL PARAMETERS AND DOSE VALUES

Exposure	$\frac{\phi(\text{Cu})}{\phi(\text{Au})}$	$\frac{\phi(\text{S})_f}{10^{10} \text{ n/cm}^2}$	$\frac{\phi(\text{In})_f}{10^{10} \text{ n/cm}^2}$	$\frac{\phi(\text{In})_f}{\phi(\text{S})_f}$	Indicated Dose, rad	Phantom* Dose, rad	Total Fluence, 10^{10} n/cm^2		Fast Spectrum Energy Shift	Slowing-Down Fluence Normalized to Unit Fast Fluence	
							Slowing- Down	Fast		$\frac{\phi(\text{Au})}{\phi(\text{Cu})}$	$\frac{\phi(\text{Cu})}{\phi(\text{Au})}$
Air	2.73	2.00	5.86	2.93	393	201	8.17	12.6	0.82	0.0152	0.0413
Behind Polyethylene	1.72	0.0734	0.253	3.45	26.4	18.8	1.90	0.610	0.73	0.118	0.203
Behind Iron	2.67	0.145	0.738	5.09	75.4	86.8	3.40	2.30	0.58	0.035	0.094
Front Iron	2.67	1.39	4.60	3.31	328	316	7.76	10.7	0.75	0.017	0.046

* Based on ^{24}Na activity.

TABLE 8

PERCENT DEVIATION OF ORGDP DOSIMETER VALUES FROM MEASURED VALUES

<u>Conditions of Exposure</u>	<u>Dose by Proportional Counter</u>	<u>Dose to Phantom Based on ^{24}Na Meas.</u>	<u>Fission Foil*</u> <u>Fluence Measurements</u>		
			<u>Pu</u>	<u>Np</u>	<u>U</u>
Air	+ 4.5	- 8.2	- 9.4	+ 1.5	+ 0.4
Behind Polyethylene	- 4.7	-10.5	- 0.9	- 1.9	+ 3.7
Behind Iron	- 2.2	+12.5	-14.2	-11.6	+ 5.3
Front Iron	+10.0	+ 6.0	+ 8.2	+ 7.8	+12.4

* Calculated fission foil values/1.15 compared with measured values.

TABLE 9

FACTORS REFLECTING SPECTRAL VARIATIONS

<u>Conditions of Exposure</u>	<u>Dose Per Unit Sodium Activation in Phantom, rad/dis/sec/ml</u>	<u>Fraction of Sodium Activation Due to Slowing-Down Neutrons</u>	<u>Fraction of Dose Due to Slowing- Down Neutrons</u>	<u>Ratio of Indium to Sulfur Fluence for Fast Spectrum</u>
Air	4.12	0.35	0.13	2.93
Behind Polyethylene	2.43	0.67	0.41	3.45
Behind Iron	2.38	0.54	0.29	5.09
Front Iron	3.34	0.37	0.15	3.31

TABLE 10
SENSITIVITIES OF DETECTORS

Detector	Zero Time ct/min/g for 75.6 Rad Dose	Detect. Weight g	Zero Time c/min/detect. (75.6 rad)	Zero Time ct/min/rad	T Assumed Counting Delay hr	ct/min/rad at Time T	Bkg. ct/min	Variations in Dose Values Corresponding to Individual Limits of Error*		
								L.E. for 1 Rad Dose	Dose in Air	Dose to Phantom From ^{24}Na Analysis
Au - Cd	3.10×10^4	0.57	1.77×10^4	234	4.0	224	240	10%	1.1%	0.8%
Cu	1513	4.6	6950	92	4.0	74	210	26.3%	3.4%	7.9%
In	5.52×10^3	10	5.32×10^4	730	13.5	91	80	15.3%	19.6%	3.2%
Sulfur										
Disc	8.55	22	183	2.49	12	2.43	22			
Burned	184	22	4048	53.5	12	52.2	22	16.5%	5.7%	0.001%

* Five-minute counting times for sample and background.

ACKNOWLEDGEMENTS

The author wishes to express his deep appreciation to Dr. John P. Butler, Atomic Energy of Canada Limited, Chalk River, Ontario for making available data on indium cross sections prior to publication.

DWG. NO. G-64-132

Figure 1
PARTS OF ORGDP DOSIMETER

Figure 2
PHOTOGRAPH OF PARTS OF ORGDP DOSIMETER

Figure 3
ASSEMBLED DOSIMETER

NOTE: These cross section values were supplied by Dr. John P. Butler, Atomic Energy of Canada, Ltd. They represent preliminary values in that corrections, amounting to possibly 2 or 3%, were yet to be applied at the time they were made available.

Figure 4
 $^{115}\text{In}(n, n')$ ^{115m}In CROSS SECTION

Figure 5
HPRR NEUTRON SPECTRUM BEHIND 30-CM THICK POLYETHYLENE SHIELD

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Figure 6
EFFECTIVE CROSS SECTIONS FOR FISSION FOILS
SHIELDED BY $1.65 \text{ g/cm}^2 \text{ }^{10}\text{B}$

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Figure 7
SULFUR RESPONSE TO SLOWING-DOWN NEUTRONS

Figure 8
NEPTUNIUM, INDIUM, AND URANIUM
RESPONSE TO SLOWING-DOWN NEUTRONS

Figure 9
PLUTONIUM RESPONSE TO SLOWING-DOWN NEUTRONS

Figure 10
INTEGRAL DOSE FOR SLOWING-DOWN SPECTRUM

Figure 11
INTEGRAL DOSE FOR SHIFTED FISSION SPECTRA

Figure 12
CAPTURE INTEGRAL FOR SLOWING-DOWN NEUTRONS

Figure 13
CAPTURE INTEGRAL FOR SHIFTED FISSION SPECTRA

Figure 14
CAPTURE INTEGRAL FOR NEUTRONS BELOW PLUTONIUM THRESHOLD

Figure 15
RESPONSES OF DETECTORS WITH SHIFTED FISSION SPECTRA

Figure 16
TOTAL FLUENCE IN FAST SPECTRUM

Figure 17
TOTAL FLUENCE IN SLOWING-DOWN SPECTRUM

Figure 18
ENERGY-SHIFT FACTOR AS A FUNCTION OF
INDIUM/SULFUR FAST FLUENCE RATIO

Figure 19

SPECTRUM 3 METERS FROM HP RR IN AIR

Figure 20
SPECTRUM IN FRONT OF IRON SHIELD

Figure 21

SPECTRUM BEHIND IRON SHIELD

Figure 22

SPECTRUM BEHIND POLYETHYLENE SHIELD

APPENDIX I

RESONANCE INTEGRAL OF COPPER AS DETERMINED WITH BROOKHAVEN BEAM

The resonance integral of copper was determined from measurements obtained at Brookhaven to establish the $1/E$ character of the neutron spectrum used for calibrating the resonance detectors of the ORGDP nuclear accident dosimeter. The method used was the standard relatively simple method which involves a comparison of the cadmium ratio determined for the material being tested (in this case copper) with the cadmium ratio of a substance having a well established resonance integral (gold). As shown by Baumann¹⁷, for example,

$$\left(\frac{I}{\sigma_m}\right)^{\text{Sample}} = \left(\frac{I}{\sigma_m}\right)^{\text{Ref}} \frac{(CR - 1)^{\text{Ref}}}{(CR - 1)^{\text{Sample}}},$$

where

$$I = \text{resonance integral} = \int_{E_0}^{\infty} \sigma_a(E) \frac{dE}{E}$$

E = neutron energy

$\sigma_a(E)$ = activation cross section at energy E

σ_m = activation cross section for a Maxwell flux distribution in the thermal energy region = $g \sigma_0$, where g is a correction factor for deviations of the cross section from a $1/v$ form in the thermal energy region, and σ_0 is the 2200 m/sec cross section¹⁸; $\sigma_0 = 98.8$ barns for gold¹⁹, 4.5 barns for copper⁸; $g = 1.006$ for gold²⁰, 1.000 for copper

CR = cadmium ratio (ratio of activation of bare foil to cadmium-covered foil).

The gold used was in the form of gold leaf (96% gold, 2.4% silver, 1.6% copper) approximately 0.2 mg/cm² thick which was cemented to a nickel washer with a 1-inch-diameter hole. Calculations showed that activation of the alloying materials would have no appreciable affect on the count rate after decay of the short-lived copper and silver isotopes. After exposure, the gold leaf was cut from the center of the washer, counted, and weighed on a microbalance. The copper foils were 1.59 cm (5/8 in.) in diameter and 25.6 mg/cm² (0.0011 in.) thick. These foils were attached with cellophane tape to the back of the washers to which the gold leaf was attached, and such pairs of foils were exposed successively bare and in cadmium shields 0.0914 cm (0.036 in.) thick.

The resonance component of the resonance integral for gold was taken as 1490 barns¹⁹. To this must be added 44 barns for the $1/v$ component, this corresponding to a 0.5-ev cadmium cut-off energy with 0.036-inch-thick cadmium in a beam geometry (Ref. 17, p. 43). Corrections to be applied to the experimental arrangement are those for self-protection in the foil and shielding of neutrons at the resonance energy by the cadmium shield.

The self protection effect for gold was calculated by Jirlow and Johansson to amount to only 4 barns for a 0.1-mg/cm²-thick foil, and it was assumed that the correction for the 0.2-mg/cm² foils used in the present experiment would be twice this.

The correction for reduction of the resonance response by the cadmium shield was calculated from data given by Martin concerning correction factors for cadmium-covered foil measurements²¹. Martin's method was to obtain measurements with varying cadmium thicknesses and extrapolate the resulting curve (nearly a straight line on a semilogarithmic graph) to zero cadmium thickness. His results indicated a 2% reduction in the gold response by 0.040-inch-thick cadmium with gold foils approximately 240 mg/cm² thick in an isotropic neutron flux. Part of this reduction would be associated with changes in the effective cadmium cut-off energy, and this would be accentuated in Martin's case since in thick foils the resonance response is reduced drastically as a result of self shielding, whereas the $1/v$ response is affected only slightly. Baumann¹⁷ gives a self-protection factor of 0.202 for 240-mg/cm²-gold foils, which indicates an effective resonance activation integral of 309 barns for gold in this thickness. The change in the cadmium cut-off energy associated with a change of 0.040-inch cadmium (0.030 to 0.070 in.) accounts for a change of 4.2 barns in the $1/v$ response, or to 1.36% of the total effective resonance integral for 240-mg/cm² foils. Martin's value of 2% for the total shielding effect of cadmium exceeds this by 0.64%, and this difference was attributed to shielding of the resonance response. Since, with equal thicknesses of cadmium, this effect would be only about half as great in a beam incident normal to the cadmium shield and would be essentially linear with thickness over the narrow range involved, the correction for 0.036-inch-thick cadmium used in the present experiment was considered to be only 0.3%. With these corrections, the total resonance activation integral of gold is 1521 barns.

The cadmium ratios were 3.775 for gold and 40.11 for copper, yielding a total copper-63 resonance integral of 4.886 barns. The $1/v$ portion of the copper response for a 0.5-ev cadmium cutoff is 2.025 barns, giving a value of 2.861 barns for the resonance response. Dahlberg et. al.⁸ calculated that the correction for scattering and self absorption of neutrons in 0.002-cm-thick copper foils amounted to 4%. Assuming the correction to be linear with thickness over the small differences involved, the correction for the 0.0029-cm-thick foils of the present experiment would be 5.8%. This yields a corrected resonance integral of 3.03 barns, which is in excellent agreement with the value 3.09 barns obtained by Dahlberg et. al. In Dahlberg's work the spectrum in the beam was accurately known from measurements with a fast chopper, so

corrections could be made for the deviation of the flux from $1/E$ dependence. The close agreement thus indicates the beam from the Brookhaven reactor was very close to $1/E$.

Flux calculated from the thin gold foil measurements showed a thermal flux of 1.395×10^{10} n/cm²/min and a resonance flux of 3.286×10^8 n/cm²/min per unit logarithmic energy interval. The corresponding counts on the resonance detectors of the ORGDP dosimeter were 2.11×10^5 (counts/min/g)/min irradiation for the cadmium difference on the gold detectors, 0.134×10^7 (counts/min/g)/min irradiation for the cadmium covered gold, and 2.70×10^3 (counts/min/g)/min irradiation for the copper shells, this last figure including a 2% correction for the variation from $1/E$ spectrum as indicated by the copper resonance integral measurement. These values yield the calibration factors shown in table 2.

APPENDIX II

UTILIZATION OF DOSIMETER RESULTS

Methods for interpreting results from the detectors of the dosimeter are described in detail in this appendix, and are illustrated with the measurements obtained behind the 12.7-cm-thick iron shield at the ORNL DOSAR Facility.

Calculation of Fluence

Fluences are calculated from the count rates of the various detectors with the calibration factors given in table 2; count rates and the corresponding fluence values are given in table 11. The concentration of ^{24}Na in the phantom solution having 1.5 mg Na/ml was 15.2 dis/sec/ml, which corresponds to 32.4 dis/sec/ml for a concentration of 3.2 mg/ml.

Response of Fast Neutron Detector to Slowing-Down Neutrons

The apparent fluence as based on a simple threshold type interpretation of the response of a fast-neutron detector may be defined by the equation:

$$\phi_a = \frac{\int_0^\infty \sigma(E) \phi(E) dE}{\sigma_{\text{Eff}}} = \frac{\int_{-\infty}^\infty \sigma(E) \phi(\ln E) d\ln E}{\sigma_{\text{Eff}}}$$

where ϕ_a = apparent fluence
 $\sigma(E)$ = fluence per unit energy
 σ_{Eff} = effective cross section

As noted in the body of this report, the slowing-down fluence is assumed to be represented by the equation:

$$\phi(\ln E) = (\phi_0 + k \ln E) F.$$

Thus, the apparent fluence $\phi(X)_s$ indicated by a fast-neutron detector X, exposed to neutrons with a slowing-down spectral distribution is:

$$\phi(X)_s = \frac{\int_{-\infty}^\infty \sigma(E) (\phi_0 + k \ln E) F d\ln E}{\sigma_{\text{Eff}}}.$$

This expression was evaluated numerically for each of the fast-neutron detectors and for a number of slowing-down spectra having various assigned values of k. For each of the spectra the fluence per unit $\ln E$ was also calculated for energy values of 4.9 and 580 ev. As noted in the

body of the report, it is considered that the activities of the copper and cadmium-covered gold detectors will yield experimental values for the fluence at these energies. Accordingly the fluence per unit $\ln E$ at 4.9 ev is designated as $\phi(\text{Au})$, and that at 580 ev as $\phi(\text{Cu})$. For each value of k , $\phi(\text{Cu})/\phi(\text{Au})$ was calculated, and the ratio $\phi(X)_s/\phi(\text{Au})$ was calculated for each of the fast-neutron detectors. The results of these calculations are shown in figures 7, 8, and 9, where the ratios $\phi(X)_s/\phi(\text{Au})$ are shown as functions of $\phi(\text{Cu})/\phi(\text{Au})$.

In the example, it is desired to determine what parts of the sulfur and indium responses were attributable to slowing-down neutrons. These values are calculated as follows:

$$\frac{\phi(\text{Cu})}{\phi(\text{Au})} = \frac{0.216 \times 10^{10}}{0.081 \times 10^{10}} = 2.67.$$

$$\phi(\text{S})_s = \frac{\phi(\text{S})_s}{\phi(\text{Au})} \times \phi(\text{Au}) = 0.515 \times 0.081 \times 10^{10} = 0.042 \times 10^{10} \text{ n/cm}^2.$$

$$\phi(\text{In})_s = \frac{\phi(\text{In})_s}{\phi(\text{Au})} \times \phi(\text{Au}) = 2.20 \times 0.081 \times 10^{10} = 0.178 \times 10^{10} \text{ n/cm}^2.$$

Values for the ratios $\phi(\text{S})_s/\phi(\text{Au})$ and $\phi(\text{In})_s/\phi(\text{Au})$ are taken from figures 7 and 8, respectively.

The responses of sulfur and indium to the slowing-down part of the spectrum determined in this way were then subtracted from the total measured responses to obtain values applicable to the fast spectrum.

$$\begin{aligned} \phi(\text{S})_f &= \phi(\text{S}) - \phi(\text{S})_s = 0.187 \times 10^{10} \text{ n/cm}^2 - 0.042 \times 10^{10} \text{ n/cm}^2 \\ &= 0.145 \times 10^{10} \text{ n/cm}^2. \end{aligned}$$

$$\begin{aligned} \phi(\text{In})_f &= \phi(\text{In}) - \phi(\text{In})_s = 0.916 \times 10^{10} \text{ n/cm}^2 - 0.178 \times 10^{10} \text{ n/cm}^2 \\ &= 0.738 \times 10^{10} \text{ n/cm}^2. \end{aligned}$$

Thus, the indium-to-sulfur fluence ratio as applied to the fast portion of the spectrum only is:

$$\frac{\phi(\text{In})_f}{\phi(\text{S})_f} = \frac{0.738 \times 10^{10} \text{ n/cm}^2}{0.145 \times 10^{10} \text{ n/cm}^2} = 5.09$$

Dose Calculations

Values of the integral $\int_0^\infty \phi(E) D(E) dE$ were determined numerically for slowing-down spectra with selected values of k , and for fission spectra

shifted in energy by various constant factors. Here $D(E)$ is the first collision dose per unit fluence as given in figure 1 of NBS Handbook 63²². It is equivalent to kerma^{23,24} for a small mass of tissue in air at the point of interest. The response of indium and sulfur to the shifted fission spectra were also calculated numerically, the results of these calculations being expressed as apparent fluence resulting from a simple threshold-type interpretation of the responses of these detectors.

In figure 10 the ratio of the integral dose for a slowing-down spectrum to $\phi(\text{Au})$ is shown as a function of the copper-to-gold fluence ratio, and in figure 11 the ratio of the integral dose for a fast spectrum to $\phi(\text{In})_f$ is shown as a function of the indium-to-sulfur fluence ratio. The first collision dose for the slowing-down spectrum, D_s , and for the fast spectrum, D_f , are calculated for the example as follows:

$$D_s = \frac{\int_0^\infty \phi(E)_s D(E) dE}{\phi(\text{Au})} \times \phi(\text{Au}) = 26.8 \times 10^{-9} \text{ rad/n/cm}^2 \times 0.081 \\ \times 10^{10} \text{ n/cm}^2 = 21.7 \text{ rad.}$$

$$D_f = \frac{\int_0^\infty \phi(E)_f D(E) dE}{\phi(\text{In})_f} \times \phi(\text{In})_f = 7.27 \times 10^{-9} \text{ rad/n/cm}^2 \times 0.740 \\ \times 10^{10} \text{ n/cm}^2 = 53.8 \text{ rad.}$$

The first-collision dose for thermal neutrons is $.28 \times 10^{-10} \text{ rad/n/cm}^2$, so the thermal neutron dose, D_{Th} , is:

$$D_{\text{Th}} = .28 \times 10^{-10} \text{ rad/n/cm}^2 \times 0.271 \times 10^{10} \text{ n/cm}^2 = 0.08 \text{ rad.}$$

Total first-collision neutron dose = $D_s + D_f + D_{\text{Th}} = 75.6 \text{ rad.}$

Neutron Dose to Phantom or Personnel

As given in the report ORNL-2748, Part A², the first-collision neutron dose is related to the sodium activity in a cylindrical phantom having a 15-cm radius, as follows:

$$D = 9.5 \times 10^8 K \frac{\int_0^\infty D(E) \phi(E) dE}{\int_0^\infty \epsilon(E) \phi(E) dE},$$

where K is the sodium activity in disintegrations per sec (corrected back to the time of exposure) per cm^3 of blood serum, this expression applying to a concentration of sodium in serum (or phantom solution) of 3.2 mg/cm^3 ; $\epsilon(E)$ is the probability that neutrons of energy E will be captured in the phantom as thermal neutrons. Capture probabilities were taken from ORNL-2748, Part A; a straight-line interpolation was taken from 0.005 Mev to thermal since this region is not covered in the reference. The capture integral was evaluated numerically for both slowing-down and fast spectra. The ratio of the capture integral for

slowing-down spectra to $\phi(\text{Au})$ is shown in figure 12 as a function of the copper-to-gold fluence ratio, and the ratio of the capture integral for fast spectra to $\phi(\text{In})$ is shown in figure 13 as a function of the indium-to-sulfur fast fluence ratio. The capture integral for thermal neutrons is 0.18. Accordingly, the total capture integral is given by the expression:

$$\int_0^{\infty} \epsilon(E) \phi(E) dE = \frac{\int \epsilon(E) \phi(E)_s dE}{\phi(\text{Au})} \times \phi(\text{Au}) + \frac{\int \epsilon(E) \phi(E)_f dE}{\phi(\text{In})_f} \times \phi(\text{In})_f + 0.18 \phi_{\text{Th}}.$$

In the example:

$$\begin{aligned} \int_0^{\infty} \epsilon(E) \phi(E) dE &= 17.9 \times 0.081 \times 10^{10} + 1.60 \times 0.740 \times 10^{10} \\ &+ 0.18 \times 0.271 \times 10^{10} = 2.68 \times 10^{10}. \end{aligned}$$

The calculated dose to the phantom was therefore:

$$D = 9.5 \times 10^8 \times 32.4 \text{ dis/sec/ml} \times \frac{75.6 \text{ rad}}{2.68 \times 10^{10}} = 86.8 \text{ rad}.$$

Comparison with Proportional Counter

As noted in the body of the report, doses were measured with a proportional counter²⁵ during a low power reactor run, and these dose values were related to the burst exposures on the basis of sulfur neutron detectors placed near the reactor in each case. The dose values given include corrections for loss of counts under the proportional counter bias.²⁵ In the case taken as an example, the proportional counter indicated a dose of 77.1 rad. The 75.6-rad dose computed from the ORGDP dosimeter measurements was low by 2%, whereas the dose to the phantom was high by 12.6%. This agreement was considered to be quite satisfactory.

Calculation of Fission Foil Responses

Numerical integrations were carried out for the fission foils in the same way as described for the sulfur and indium detectors. The ratios of the apparent fluences indicated by the various detectors to the gold fluence are shown for slowing-down spectra as functions of the copper-to-gold ratio in figures 8 and 9. The ratios of apparent-fluence-to-indium-fluence are shown for fast spectra as functions of the indium-to-sulfur ratio in figure 15.

Remembering that the copper-to-gold fluence ratio in the example was 2.67 and the indium-to-sulfur fluence ratio for the fast spectrum was 5.10, the response of the plutonium fission foil was calculated as follows:

$$\begin{aligned}\phi(\text{Pu}) &= \phi(\text{Pu})_s + \phi(\text{Pu})_f = \frac{\phi(\text{Pu})_s}{\phi(\text{Au})} \times \phi(\text{Au}) + \frac{\phi(\text{Pu})_f}{\phi(\text{In})_f} \times \phi(\text{In})_f \\ &= 20.6 \times 0.081 \times 10^{10} \text{ n/cm}^2 + 2.98 \times 0.740 \times 10^{10} \\ &= 1.67 \times 10^{10} + 2.21 \times 10^{10} = 3.88 \times 10^{10} \text{ n/cm}^2.\end{aligned}$$

As noted previously, a 15% bias was assumed between the ORGDP and Hurst fluence measurements, and correcting for this yields a calculated fluence of $3.88 \times 10^{10} / 1.15 = 3.37 \times 10^{10} \text{ n/cm}^2$. The experimental plutonium fluence was $3.82 \times 10^{10} \text{ n/cm}^2$ as based on the ORNL fission-foil calibration¹⁶ and a 1.80 barn cross section for plutonium. When this is corrected to the calculated cross section of 1.75 barns, the experimental value is $3.93 \times 10^{10} \text{ n/cm}^2$. The calculated value was therefore 85.8% of the experimental value, the error being -14.2%.

Total Fluence

In figure 16 the ratio of the total fast fluence to $\phi(\text{In})_f$ is given as a function of $\phi(\text{In})_f / \phi(\text{S})_f$. As noted from this figure, the total fast fluence is 3.13 times the fast indium fluence with an indium-to-sulfur fast fluence ratio of 5.09. The total fluence in the fast spectrum corresponding to $\phi(\text{In})_f$ of $0.738 \times 10^{10} \text{ n/cm}^2$ is thus $2.31 \times 10^{10} \text{ n/cm}^2$.

Similarly, the total fluence in the slowing-down spectrum as determined from figure 17 is 42 times the gold fluence with a copper-to-gold fluence ratio of 2.67. The total fluence in the slowing-down spectrum corresponding to $\phi(\text{Au})$ of $0.081 \times 10^{10} \text{ n/cm}^2 / \ln E$ is $3.40 \times 10^{10} \text{ n/cm}^2$.

Graphical Representation of Spectrum

In order to represent spectra graphically, all spectra were normalized to unit fluence in the fast part of the spectrum. This gives the following values for the normalized spectrum:

$$\begin{aligned}\phi_f \text{ total} &= 1.00 \text{ n/cm}^2. \\ \phi(\text{Au}) &= 0.0350 \text{ n/cm}^2 \text{ per unit } \ln E \text{ at } 4.9 \text{ ev.} \\ \phi(\text{Cu}) &= 0.094 \text{ n/cm}^2 \text{ per unit } \ln E \text{ at } 580 \text{ ev.}\end{aligned}$$

The factor by which the fast spectrum was shifted from fission energies was determined from figure 18 as 0.58. The normalized fission spectrum, for which values are listed in table 12, was plotted with energies reduced

by this factor. Normalized values for the slowing-down spectrum were then plotted at 4.9 and 580 ev, and a straight line was extended through them. Values taken from this line were then multiplied by the appropriate fraction of neutrons originating in the fission spectrum at higher energies, also listed in table 12, and the products were plotted to yield the slowing-down spectrum. The values for the fast and slowing-down spectra were then added to yield the curve for the total spectrum.

Spectra developed in this way are shown in figures 19 through 22.

TABLE 11
FLUENCE DETERMINATIONS

Detector	Count Rate*	Fluence	Symbol For Fluence Value
Gold-Bare	6.97×10^4 ct/min/g		
Gold-Cd	3.10×10^4 ct/min/g	0.081×10^{10} n/cm ² /ln E at 4.9 ev.	φ(Au)
Cd Difference	3.87×10^4 ct/min/g	0.271×10^{10} n/cm ² nominal thermal fluence	φTh
Copper	1513 ct/min/g	0.216×10^{10} n/cm ² /ln E at 580 ev.	φ(Cu)
Indium-115m	$5.52 \times 10^4 \frac{\text{ct/min}}{10 \text{ g sphere}}$	0.916×10^{10} n/cm ² > 1.5 Mev	φ(In)
Sulfur Disc	$188 \frac{\text{ct/min}}{\text{disc}}$	0.187×10^{10} n/cm ² > 2.9 Mev	φ(S)
Burned	184** ct/min/g	0.187×10^{10} n/cm ² > 2.9 Mev	φ(S)

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* Corrected for radioactive decay to time of exposure.

** Calculated from counts on solid discs.

TABLE 12
WATT FISSION SPECTRUM

<u>Mev</u>	Fluence per Unit Energy $\phi(E)$	Fluence per Unit $\ln E$ $\phi(\ln E)$	$\int_E^\infty \phi(E) dE$
0.01	0.0679	0.00068	
0.04	0.1132	0.00547	
0.1	0.2023	0.0202	0.9860
0.2	0.2676	0.0535	0.9623
0.3	0.3068	0.0920	0.9337
0.4	0.3300	0.132	0.9013
0.5	0.3450	0.173	0.8679
0.75	0.357	0.268	0.779
1.00	0.3446	0.345	0.6918
1.5	0.295	0.443	0.532
2.0	0.2371	0.2742	0.3972
2.1	0.2258	0.4742	0.374
2.5	0.1839	0.460	0.2927
2.9	0.147	0.425	0.225
3.0	0.1384	0.415	0.2124
4.0	0.07472	0.299	0.1086
5.0	0.03847	0.192	0.0537
6.0	0.01916	0.115	0.0261
7.0	9.316×10^{-3}	0.0652	0.0124
8.0	4.423×10^{-3}	0.0354	0.0057
9.0	2.076×10^{-3}	0.0187	0.0027
10.0	9.53×10^{-4}	0.0095	0.0012

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