HEALTH PHYSICS

OFFICIAL JOURNAL OF THE HEALTH PHYSICS SOCIETY

Volume 9, 1963

KARL Z. MORGAN
Editor-in-Chief

W. S. SNYDER   J. A. AUXIER
Editors

PERGAMON PRESS   NEW YORK   OXFORD

DOSIMETRY INVESTIGATION OF THE RECUPLEX CRITICALITY ACCIDENT*

Hanford Laboratories,† General Electric Company, Richland, Washington

(*Received* 10 *September* 1962; *in revised form* 4 *February* 1963)

Abstract—Twenty four persons were involved in a criticality accident that occurred in the Recuplex facility at Hanford. The principal sources of information concerning the exposure of these individuals were personnel meters for the gamma rays and whole body counts and blood activation measurements for the neutrons. Additional information was obtained from measurements of P^{32} in hair and of radioactivity in objects that were on the persons involved and from threshold detectors and recording instruments in the building. Three persons were close to the critical vessel. One of these received the highest doses observed, namely 23–30 rad from fast neutrons and 63 r to the central part of the body with 42–54 rad from fast neutrons to his eyes.

INTRODUCTION

At 10.59 am (PST), Saturday, April 7, 1962 a criticality accident occurred in a plutonium waste chemical recovery facility at the Hanford Atomic Products Operation, operated for the Atomic Energy Commission by the General Electric Company. Four men were hospitalized but were released after medical observation and after estimates of the radiation doses received were available. This report describes the dosimetry investigation that was made following the accident. This investigation was facilitated by the fact that all employees affected had personnel dosimeters in their possession when the incident occurred. The interpretation of the data supplied by these dosimeters was supplemented by information gathered by techniques that were developed in connection with other accidents. Below, the available information is first presented and then applied in a discussion of the dosimetry of the people involved in the accident.

*Work performed under contract No. AT (45-1)–1350 between the Atomic Energy Commission and General Electric Co.

†This report was prepared by a committee consisting of C. C. Gamertsfelder, H. V. Larson, J. M. Nielsen, W. C. Roesch (Chairman) and E. C. Watson. It reports the work of a number of people at Hanford.

DESCRIPTION OF THE ACCIDENT

The accident occurred in a facility known as Recuplex within a building known as the 234-5 Building. When the accident occurred, there were twenty-two persons in the 234-5 Building. The criticality alarm siren started almost at once (several people reported that air-proportional alpha contamination monitors broke down slightly before the siren sounded). All persons in the 234-5 Building evacuated to a gate house (2701-Z) about 100 yd from 234-5 and then took shelter behind another building (2704-Z) when the former area was found to have an exposure rate of about 200 mr/hr. Within 5–10 min they had evacuated these areas in the evacuation bus or by private car. Two patrolmen, stationed in the gate house at the time of the excursion, increased the total number of evacuees to twenty-four.

The evacuees went to the first aid building for the area (except for one who went to the area badge house and was directed to first aid). By this time the employees who had been in the Recuplex area and had seen the Cerenkov radiation flash were known; however, all employees were given a "Quick Sort" examination to determine who had been exposed to significant fast neutron doses.[1] The counting rate of a Geiger counter held at their abdomen was observed while the person bent over around the counter. Only those employees who had been in the Recuplex area gave significant readings.

Contamination surveys of the evacuees were also made while they were at the first aid building. No contamination was found. Their personnel dosimeters were collected for examination. Personal effects were examined for radioactivity and then sent in for laboratory study. The first blood and hair samples and excreta collections were made.

After examination and treatment at Kadlec Hospital, four persons, including the three most highly exposed, were sent to the Hanford Whole Body Counter for examination. The next day all but one of the remaining evacuees were also examined at the Counter; the last man was examined the following day. Whole body counts and blood and excreta collection were repeated on the most highly exposed persons until no radioactivity of interest was detectable.

Information was obtained immediately from each employee to establish where he had been when the criticality alarm sounded and how he left the building. Detailed personal interviews

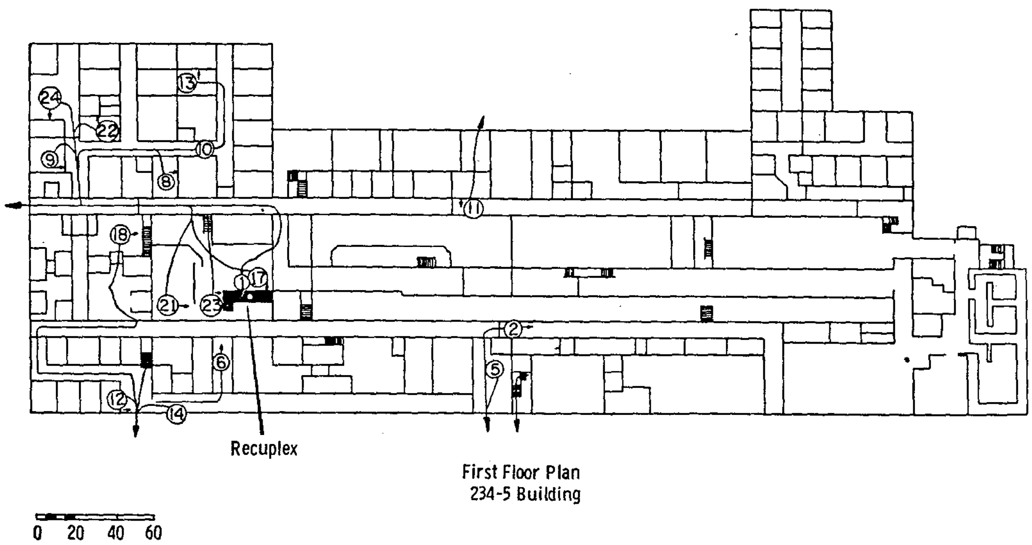

FIG. 1. Routes followed by employees evacuating the 234–5 building (first floor).

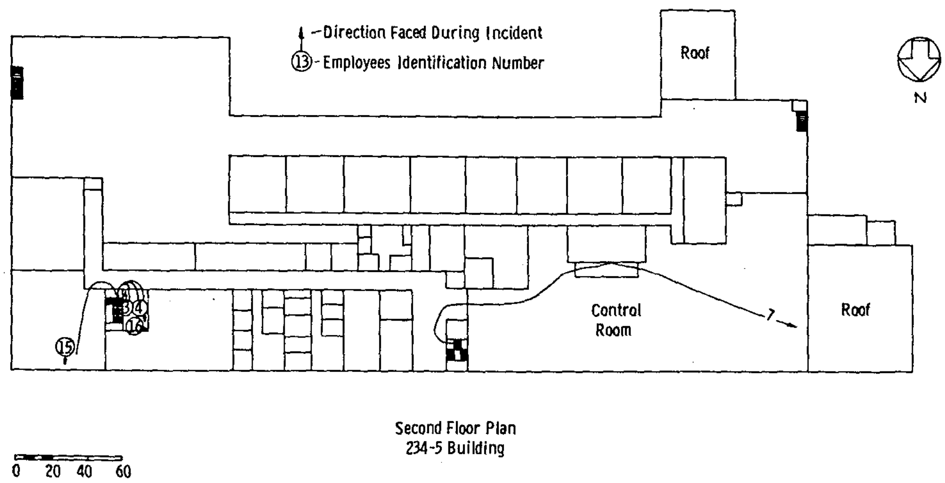

FIG. 2. Routes followed by employees evacuating the 234–5 building (second floor).

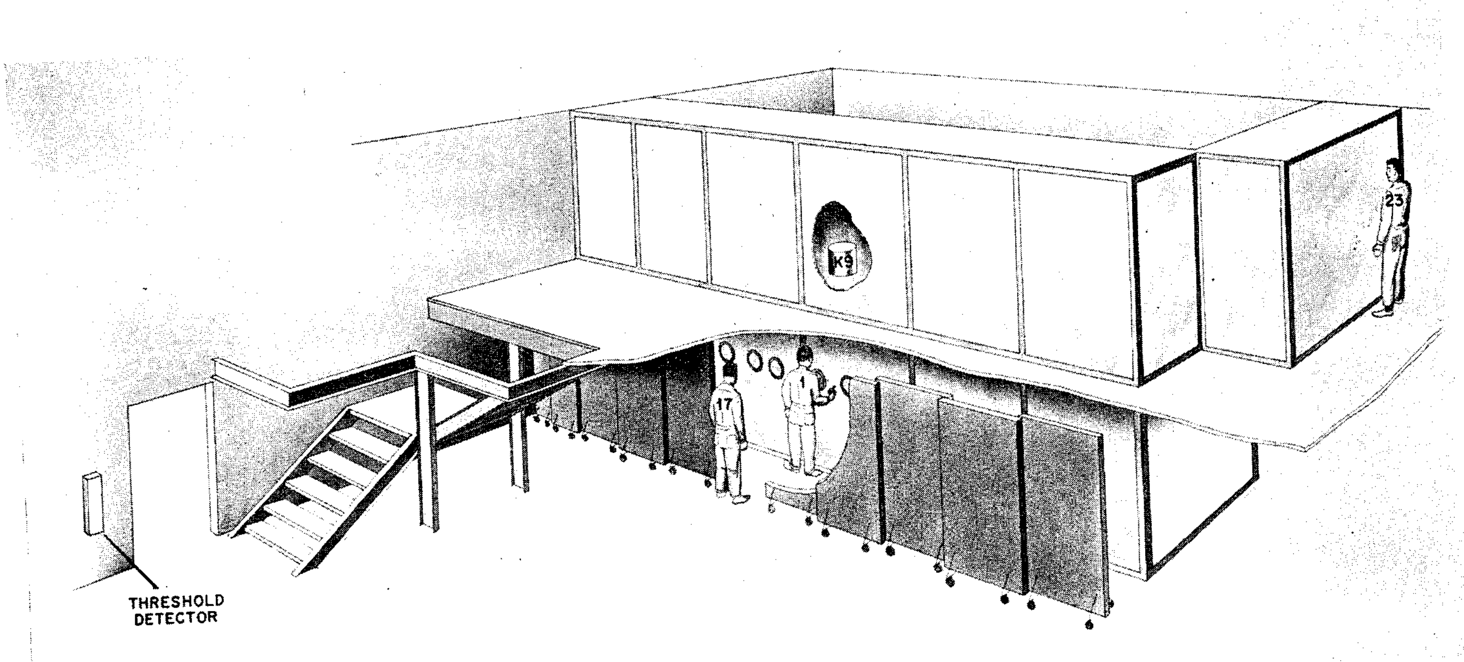

FIG. 3. Positions of employees in the recuplex area at the time of the accident. The position of the threshold dosimeter is also shown.

were made during the following week. All but five people in the 234-5 Building evacuated immediately upon hearing the siren; all but one had left within about 2 min; the last man was out within 4 min. The routes each one followed in leaving the building are shown in Figs. 1 and 2.

Information for the three most highly exposed persons was made as detailed as their recollections would allow. Figure 3 shows where these people were standing at the time they saw the Cerenkov radiation flash. Employee #1 was standing immediately below the critical vessel, the K-9 Tank, manipulating a valve at the face of the hood containing the tank. His body was very close to the hood wall. His eyes were about 5 ft from the center of the K-9 Tank; the parts of the trunk of his body were between 6 and 8 ft away. Employee #17 was standing about 2 ft to the side and about 5 ft behind Employee #1. There was a movable lead shield behind #1, but #17 was in full view of #1 and of the K-9 Tank. #17's eyes were about 10 ft from the center of K-9 and the trunk of his body was 10–11 ft away. The K-9 Tank is cylindrical with a capacity of 69 l.; it contained about 45 l. when the excursion occurred. The tank has a Pyrex wall about 3/8 in. thick and a steel bottom plate about 1 in. thick. #1 and #17 were exposed to radiations coming through both the wall and the bottom. The only other materials between them and the tank were the $\frac{1}{2}$-in. thick lucite hood walls and some plumbing inside the hood. Employee #23 was standing in front of another hood about 26 ft from the center of K-9. Most of the radiation reaching him probably came through the sides of the tank. The only materials between him and K-9 were the lucite walls of the hood containing K-9 and the hood he was facing and the thin metal back of the latter.

Of the next two most highly exposed people, Employee #6 was about 30 ft from K-9 with one concrete wall about 4 in. thick and one metal partition wall in between. This employee delayed to lock up some classified documents but was outside the building in about 25 sec. Employee #21 was about 40 ft away and was shielded by an 8-in. thick concrete wall.

Before considering the measurements made for each individual, information of general interest can be obtained from instruments that were near the scene of the accident. Two recording BF_3 counters (one for high levels, one for low) were operating at the time of the accident in an incinerator room in the 234-5 Building. The data from the chart recorders are plotted in Fig. 4. They indicate an initial excursion the exact magnitude of which cannot be determined because the flux level is recorded only every 30 sec and it may be expected to vary by orders of magnitude within such a time period. Following this initial pulse which presumably activated the criticality alarm there was a continuing nuclear reaction of a magnitude sufficient to keep the recorder off-scale for a period of about 30 min. After the recorder returned to on-scale readings the fissioning continued at a generally reduced rate till 36 hr after the incident began. It appears that those in a position to be most seriously exposed to the critical vessel evacuated in time to limit their exposure to only a part or all of the initial excursion.

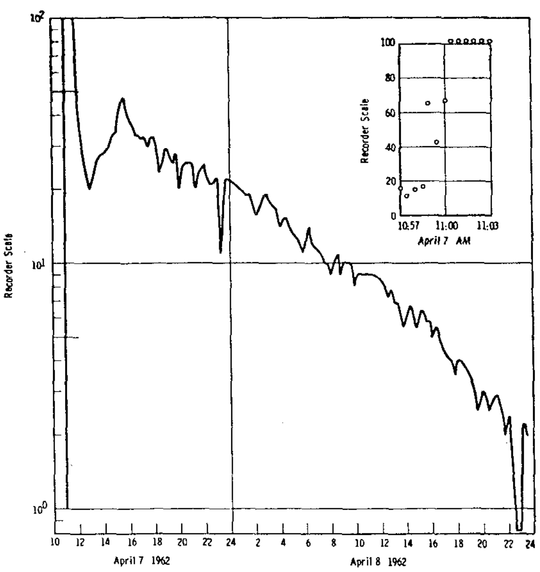

FIG. 4. Data from a recording BF_3 counter operating in the 234–5 building at the time of the accident.

A threshold detector[2] was located about 26 ft from the critical vessel. Its position is shown in Fig. 3. At least one of the steel beams of the stairway shown in the figure was on the

Table 1. *Threshold detector results*

Neutron energy band	n/cm²	Relative* n/cm²	Relative* dose
Thermal	1.17×10^{10}	0.39	0.005
1–750 KeV	1.26×10^{10}	0.42	0.25
0.75–1.5 MeV	1.05×10^{10}	0.35	0.40
1.5–2.5 MeV	0.34×10^{10}	0.11	0.15
>2.5 MeV	0.35×10^{10}	0.12	0.20

* Relative to n/cm² or to dose for neutrons above 1 KeV.

line-of-sight between the vessel and the dosimeter. The metal grid floor of the mezzanine level, the stairway, and another hood at the head of the stairs provided masses of material in which radiation from K-9 could scatter and then reach the detector. These certainly influenced the relative spectra of the neutrons reaching the detector as compared to those reaching the men. For lack of other information, however, the spectrum received by the detector was used in analyzing other pertinent data. The detector was removed about 96 min after the accidental

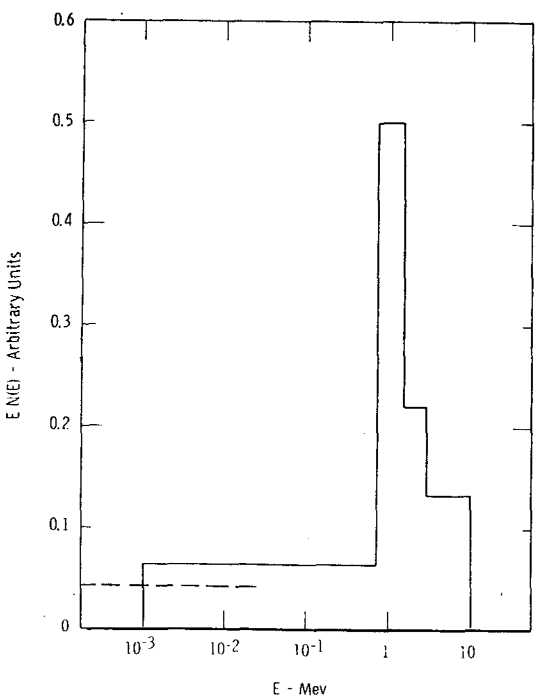

FIG. 5. Spectrum measured with threshold detector during recuplex accident.

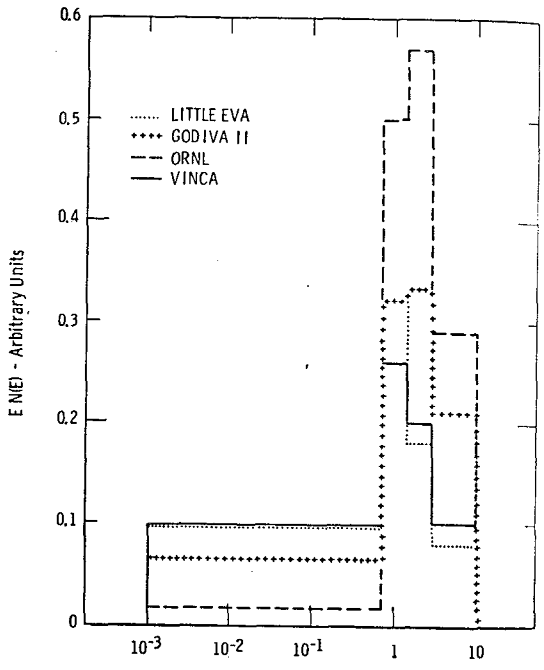

FIG. 6. Experimental spectra measured with threshold detectors.

excursions started so it was present during the large excursion shown in Fig. 4 as well as during the time the people were present.

The results obtained from analysis of the threshold detector are given in Table 1. The results relative to the neutrons/cm² measured with the plutonium foil are also given. As described in the Ref. (2), the shielded plutonium foil is assumed to measure the neutrons above 1 KeV. The number spectrum is presented in Fig. 5. For comparison several other spectra obtained with threshold detectors [(3–5)] and normalized in the same way are shown in Fig. 6. Figure 7 shows histograms prepared from calculated spectra;[(6)] since information is lost in going from the calculated spectra to the histograms, the original normalized spectra are given in Fig. 8. There is not close agreement between the present spectrum and any of the others, but the general features are the same and the differences are of the sort to be expected if the present results include the effects of a significant number of scattered, and hence lower energy, neutrons. Table 1 also contains the dose spectrum

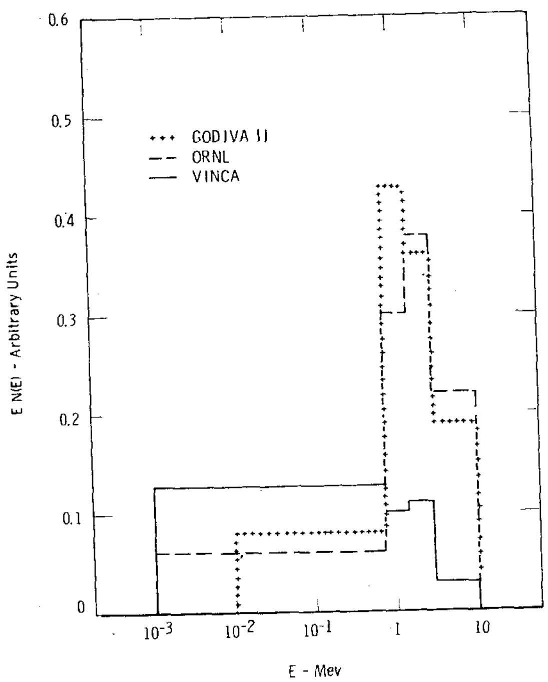

FIG. 7. Theoretical spectra (histograms) calculated for threshold detectors.

normalized to unit dose for the neutrons above 1 KeV.

The threshold detector was calibrated and interpreted in a different manner[7] from that described in the original reference.[2] In the present case the fast neutron calibrations were made in known fluxes of fast neutrons rather than with thermal neutrons. The intermediate neutron energy spectrum was estimated from the activation in the gold and cadmium-covered gold foils in the detector. If ϕ_{th} was the thermal neutrons/cm^2 and if σ_{2200} is the activation cross section of gold for neutrons whose velocity is 2200 m/sec, then the difference in activity of the two foils is proportional to $\frac{1}{2}\sqrt{\pi}\,\sigma_{2200}\phi_{th}$. If the intermediate neutron flux is assumed to be given by $k\phi_{Pu}/E$, where E is the neutron energy, k is a constant, and ϕ_{Pu} the flux measured by the shielded plutonium foil, then the activation of the cadmium covered foil is proportional to

$$k\phi_{Pu}\int \sigma_{act}\ (dE/E)$$

where the integral is over the activation cross section of gold. Measured foil activities of 1.6 and 1.0 $\times$ 10^6 disintegrations/min, Hughes'[8] values of the cross sections, and flux ratios from Table 1 give $k = 0.042$. This is shown as a dashed line in Fig. 5 and is in good agreement with the spectrum determined with the threshold foils.

PERSONNEL DOSIMETERS

Each of the persons near the critical vessel* at the time of the accident was wearing his Hanford Film Badge Dosimeter.[9] The dosimeters had last been exchanged 15 days before the accident; therefore, particularly for the smaller doses, a significant part of the darkening of the film may have been produced during employment prior to the accident.

The exposures of Employees #1, #17, and #23 were so great that the developed sensitive (508) film from their dosimeters was too dark to permit optical density measurements. The

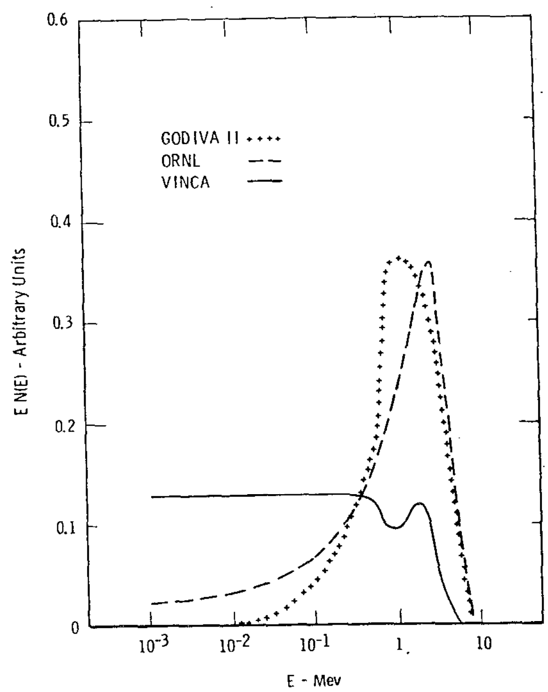

FIG. 8. Theoretical spectra from which the histrograms of Fig. 7 were prepared.

* Two patrolmen stationed in the gate house received negligible doses and are not considered further in this report.

insensitive (1290) film from their dosimeters was used. Because of slow neutron activation of the aluminum and silver absorbers in the dosimeters, there was additional darkening of the areas of the dosimeters covered by them so the usual interpretation methods could not be used. The exposure doses were determined from the densities of the unshielded portion of the dosimeter (the open window). There is an uncertainty in doing this[10] because during both exposure and calibration the film is affected by secondary electrons produced by the photons in the environment of the dosimeter as well as in the material of the dosimeter itself. In the present case the density measured under the open window could have been as much as 15 per cent too low because of this effect. The dosimeter contains a lead strip in which the payroll number and other information is punched. For the films in question there was enough unused area under the lead tape to take a densitometer reading. These readings were compared with similar readings on the calibration films; they gave exposure dose estimates that confirmed those from the open window readings. In making this comparison it is assumed that there is no appreciable slow neutron activation of the lead tapes and no effect due to different photon spectra.

Some of the darkening of these films must have been due to neutron activation of the materials in the emulsion. It has been reported[11] that 0.13 rad of thermal neutrons or about 40 rad of fast neutrons (first collision dose) would produce the same darkening of 1290 film as 1 r of Co^{60} gamma rays. For example, if the exposure of Employee #1 was 25 rad of fast neutrons plus 0.5 rad of thermal neutrons, the darkening predicted would be equivalent to 4.5 r of gamma radiation. This is 7 per cent of the exposure dose measured as described above.

The dosimeters of the other people in the 234-5 Building were, where necessary, read by these same methods but with the 508 film. The results of all the film badge dosimeter measurements are given in Table 2. No corrections have been made for the neutron darkening just mentioned.

Employees #21 and #23 were wearing neutron film badge dosimeters.[12] In each case the nuclear track plate was so darkened by the photon exposure that recoil tracks could not be identified. In the case of #23, approximate readings of the 508 film in the dosimeter could be made. They indicate an exposure dose of about 10 r, in agreement with his regular dosimeter, and about 3.5×10^9 neutrons/cm² of thermal neutrons.

Table 2. *Personnel dosimeter results* (*all exposures in r*

Employee	508 Film	1290 Film	Neutron film	Finger ring
#1		63		80
2	0.03			
3	0.12			
4	0.15			
5	0.02			
6	0.98			
7	0.04			
8	0.10			
9	0.05			
10	0.06			
11	0.07			
12	0.20			
13	0.13			
14	0.70			
15	0.20			
16	0.1			
17		23		
18	0.40			
21	1.0			
22	0.05			
23		13	10	5.7
24	0.02			

Employees #1 and #23 were wearing film ring dosimeters. These indicated exposures of 80 and 5.7 r, respectively.

Two additional studies were made with the personnel dosimeters of Employees #1, #17, and #23. The very dark 508 films were exposed to slow neutrons and measurements of the activation of the developed silver used as a measurement of the gamma ray exposure dose.[13,14] The activation of the films was done in the large moderator used for producing slow neutron fluxes with the Van de Graaff accelerator.[15] The radioactivity was easily measurable,[16] but it was found that the three films were at or very near the first maximum of the curve of activity versus dose for the calibration film.[17] It was not possible to get accurate exposure estimates. The same slow neutron facility was used to

Table 3. Thermal neutron estimates from film badges

Employee	Thermal neutrons/cm²	Estimated uncertainty
#1	2.3×10^{10}	10%
#17	6.5×10^{9}	50%
#23	3.1×10^{9}	200%

estimate the neutron flux density that had produced the excess darkening on the 1290 film behind the silver shields. Fresh films were exposed to gamma ray doses in the range of those to which the people were exposed and then exposed to slow neutrons until the total flux density producing the same density pattern as on the personnel film was found. The neutron flux densities found in this way were multiplied by a factor 0.79 to allow for the fact that part of the activation during the accident was due to intermediate energy neutrons. The factor was calculated from the gold foil activities in the threshold detector and the thermal neutron cross sections and resonance integrals of gold and silver[8]. The thermal neutron fields estimated by this method are given in Table 3.

WHOLE BODY COUNTING

The occupants of the 234-5 Building at the time of the accident were counted in the Hanford Whole Body Counter.[18] The measured values of Na^{24} activity, corrected for decay since the time of the accident, and the individuals' weights are given in Table 4. No correction was made for Na-24 that might have been eliminated before the counting took place; it is estimated that only a few per cent were missed in this way for those counted immediately. The quotient of the number of μc by the body weight in kg was multiplied by 215 rad-kg/μc to obtain the first collision dose to the person.

The factor 215 rad-kg/μc was obtained by averaging the following two experimental values. Measurements[19] with a burro at the mock-up of the Oak Ridge criticality accident gave 204 rad-kg/μc. An experiment with solutions of sodium salts in bottles at the Godiva II reactor gave 226 rad-kg/μc.[20]

Recently the dosimetry investigation of the Vinca critical accident was reported[5] for which an average factor of 81 rad-kg/μc was used (neglecting corrections for the weights of the individual persons). The difference between this figure and those above is due to the presence of a very large proportion of low energy neutrons near the Vinca reactor. If the threshold detector measurements reported for that reactor and those reported above for the present criticality accident are used to estimate the neutron first collision dose per unit Na^{24} activation,[21] the rad-kg/μc factor for the Hanford accident is about 2.3 times that for the Vinca, i.e. about 190 rad-kg/μc. This is satisfactorily close to the value used above. Although, as remarked above, the threshold detector measurements for the Hanford accident probably represent a different spectrum than that to which the employees were exposed because of attenuation and scattering; the comparison of the Vinca and Hanford spectra to estimate the above factor is not much affected by the difference.

It is estimated that the Na^{24} burdens were determined to an accuracy of about 5 per cent where counting data were not limited by statistics. Counting statistics became important for burdens of about 0.001 μc (before correction for decay). Those employees in whom less than

Table 4. Whole body counting results

Employee	μc Na^{24}	Weight (kg)	Neutron first collision dose (rads)
#1	7.55	70.4	23
2	0.001	85.3	<0.01
3	0.014	71.8	0.04
4	0.022	95.4	0.05
5	0.001	93.4	<0.01
6	0.088	55.3	0.34
7	0.002	68.5	<0.01
8	0.004	71.2	0.01
9	0.001	61.2	<0.01
10	0.006	71.7	0.02
11	0.001	73.5	<0.01
12	0.008	75.9	0.02
13	0.001	70.8	<0.01
14	0.034	70.3	0.10
15	0.003	67.1	<0.01
16	0.010	84.8	0.02
17	4.20	98.1	9.2
18	0.019	85	0.05
21	0.055	72.7	0.16
22	0.001	56.7	<0.01
23	1.12	82.4	2.9
24	0.001	78.9	<0.01

0.001 μc was detected were assigned a dose of less than 0.01 rad.

The presence of K^{42} was noticed in those people who had large Na^{24} burdens. The amounts present were consistent with estimates from abundance and cross-section data which indicate that there should be about one seventh as many μc of K^{42}. Employees #1, #17, and #23 were counted several more times at the body counter. The Na^{24} was observed to disappear with the expected 15-hr half-life. Each of these three men was found to have had some Au^{198} produced in fillings in his teeth. In the case of #17 the gold was in bridge-work that could be removed. This made it possible to count him with the P^{32} counter.(22) (After the original report on the counter, the detector was moved to a counting position over the head rather than over the chest in order to reduce interference by other isotopes; the presence of radioactive gold fillings would have prevented such measurements). The first count for P^{32} was made on #17 ten days after the accident. The P^{32} was easily detected. The counting rate due to the P^{32} decreased exponentially with a 14.5 day half-life (i.e. the radioactive decay half-life) rather than the 8–10 day half-life observed for subjects who receive P^{32} intravenously. This indicated that most of the P^{32} being observed was formed in the relatively tightly bound phosphorous, probably that in the skull, rather than that more mobile portion in which the intravenously injected P^{32} appears. Thus the calibration of the counter, which was done with intravenously injected subjects, was not applicable; if applied anyway, the calibration would have indicated two to three times as much P^{32} as predicted from the activity of the Na^{24} present.

Na^{24} IN BLOOD

Two 2-cm^3 blood samples each for Employees #1, #17 and #23 were counted for Na^{24}. The first samples were counted on a 3-in. well crystal scintillation counter. They had coagulated before they could be counted. The second set of samples was treated with heparin to prevent coagulation. They were counted for 30 min on a total absorption gamma-ray spectrometer.(23) The results of the two counts, corrected for decay from the time of the accident, are given in Table 5. The agreement is considered reasonably good.

Table 5. Na^{24} *in blood* (*Two samples from each employee*)

Employee	Na^{24} ($\mu c/cm^3$ blood)	Neutron first collision dose (rads)	
#1	1.5×10^{-4}	25	±2.5
	1.8×10^{-4}	30	±3.0
#17	8.8×10^{-5}	15	±2.2
	7.3×10^{-5}	12	±1.2
#23	2.0×10^{-5}	4.0	±1.2
	2.1×10^{-5}	3.4	±0.8

The activity density of the Na^{24} in the whole blood was converted to neutron first collision dose by multiplying by the factor 1.65×10^5 rad-$cm^3/\mu c$. This is the ratio of first collision dose to blood activity found in the Oak Ridge burro experiment.(19)

If the sodium in the whole body and in the blood are equally irradiated by slow neutrons or if there is rapid equilibration of the sodium throughout all compartments in the body, then this factor should be related to the factor used above with the whole body counter data. The ratio of μc/kg of Na^{24} in the body to $\mu c/cm^3$ in the blood should equal the ratio of the density of sodium in the body (105 g/70 kg for the standard man(24)) to that in the blood (1.91×10^{-3} g/cm^3(25)): $(1.91 \times 10^{-3} \times 70)/105 = 1.27 \times 10^{-3}$. $1.65 \times 10^5 \times 1.27 \times 10^{-3} = 210$ rad-kg/μc, in good agreement with the figure chosen above for the whole body counting. This comparison is significant because the blood and whole body activities of the burro were determined in different ways. A similar comparison can be made using the data obtained after the critical accident at Los Alamos. The fatally exposed employee was found to have 0.00531 $\mu c/cm^3$ of Na^{24} in whole blood and 293 μc in his whole body, which weighed 71.5 kg.(26) $(0.00531 \times 71.5)/293 = 1.30 \times 10^{-3}$ in good agreement with the above value. This latter value is particularly significant because the neutron dose distribution in the man's body was very non-uniform. The agreement between the two results indicates that the sodium had been able to equilibrate effectively throughout the body.

Table 6. Na^{24} *in Urine*

Employee	Date	Average dis./min-ml	Total ml	Total dis./min
#1	4/7/62	174.1	1685	2.93×10^5
	4/8/62	210.9	3800	8.01×10^5
	4/9/62	229.7	4340	9.97×10^5
	4/10/62	142.0	2500	3.55×10^5
	4/11–12/62	77.8	4900	3.81×10^5
	4/12–13/62	135.0	4280	5.78×10^5
#17	4/7/62	339.5	580	1.97×10^5
	4/8/62	310.7	3020	9.38×10^5
	4/9/62	185.5	3200	5.94×10^5
	4/10/62	120.0	3300	3.96×10^5
	4/11–12/62	136.8	3225	4.41×10^5
	4/12–13/62	135.0	1950	2.63×10^5
#23	4/7/62	66.7	1415	0.94×10^5
	4/8/62	44.3	3935	1.74×10^5
	4/9/62	27.8	3850	1.07×10^5
	4/12–13/62	40.5	3050	1.24×10^5

Na^{24} IN EXCRETA

The first urine samples from Employees #1, #17 and #23 were counted on a 3-in. well crystal scintillation counter. These measurements were repeated and all later samples were measured on a 5-in. well crystal scintillation counter.[27] Sample size varied from 2 to 500 cm^3 and counting time from 5 to 30 min depending on the activity of the sample. The results, corrected for decay from the time of the accident, are given in Table 6. The Na^{24} activity found in feces was negligible.

P^{32} IN HAIR

Samples of hair were taken from Employees #1, #17 and #23 from several locations on their bodies. The P^{32} was separated from the hair[28] and counted in a low background proportional counter. The sulfur content was determined for several samples by a spectrometric method and found to agree with the results of PETERSON *et al.*[29] so their value, 47.7 mg sulfur per g of hair, was then assumed for all calculations. The results are listed in Table 7. The time integral of the flux density of neutrons having energies greater than 2.5 MeV and the first collision dose due to these neutrons were calculated using the formula given by PETERSON *et al.* Their formula gives factors of 6.44×10^6 neutrons/cm^2 per dis./min-g sulfur and 0.0246 rad per dis./min-g sulfur.

RADIOACTIVITY OF OTHER OBJECTS

A variety of other objects was collected from the three principals and measured for radioactivity in a 5-in. well crystal scintillation counter.[27] Later these same objects were activated with slow neutrons in the large moderator in the same way as in the study of the film badges described above.[16] The neutron fluxes in the large moderator that produced the same activity as in the accident were corrected to allow for the intermediate energy neutron activation during the accident. The effective resonance integral for the gold in the eye frames of Employee #17's glasses was found to be 581 barns (compared to 1300 for thin foils[8]) by the cadmium ratio. Otherwise, the thin foil values were used. The thermal neutron fluxes estimated in this way are listed in Table 8.

RBE DOSE

RBE dose (in rems) is the product of the absorbed dose in rad by an agreed RBE multiplier. Its function is to provide a common, additive measurement of all radiations that expresses the radiation protection hazard involved in exposures to the radiations. NBS Handbook 59[30] recommends RBE values which are dependent upon the linear energy transfer to tissue by the charged particles generated by the radiation. These values of RBE are to be used in assessing hazards due to long continued low

Table 7. P^{32} *in hair*

Employee	Hair sample Type	cm from top of head	dis/min-g	Neutrons above 2.5 MeV Neutrons/cm²	First collision dose
#1	Head	0		2.4×10^9	9.3
	Posterior				
	Chest	33–77		2.9×10^9	11
	Pubic	87		1.8×10^9	6.9
	Leg	135–161		1.5×10^9	5.6
	(Fingernail				
	Left		24		
	Right)		37		
	(Toenails)		11		
#17	Chest	43–73		1.4×10^9	5.2
	Pubic	94		7.7×10^8	2.9
	Back	34		9.1×10^8	3.5
#23	Head	0		4.3×10^8	1.6
	Pubic	93		3.8×10^8	1.4

level irradiation. The value usually accepted for neutron irradiation is 10, but this is not applicable for the acute exposures described in this report. Indeed, one of the reasons for the careful analysis of the data provided by such accidents is to provide RBE's that might be suitable. For this reason none of the doses given in this report has been converted to an RBE dose. For purposes of administrative recording of whole body radiation exposures of the employees involved, an RBE factor of 2 for acute neutron exposure was assumed. This is largely based on extrapolation from experimental animal exposures and data from previous accidental exposures of humans.[19] The doses to the eyes were recorded with an assumed RBE of 10.[31]

CONCLUSIONS AND SUMMARY

Our primary sources of information concerning the exposure of individuals during the

Table 8. Radioactivity of other objects

Employee	Item	Location cm from top of head	Radioisotope measured	Large moderator neutrons/cm²	Thermal neutrons/cm²
#1	Silver shield from film badge	~40	Cu-64	1.49×10^{10}	1.34×10^{10}
	Ball point pen, minus tip	45	Cu-64	1.37×10^{10}	1.23×10^{10}
	Tip of ball point pen	45	Cu-64	0.99×10^{10}	0.89×10^{10}
#17	Silver shield from film badge	~40	Cu-64	0.73×10^{10}	0.66×10^{10}
	Nickel	100	Mn-56	0.48×10^{10}	0.42×10^{10}
	Belt buckle	73	Cu-64	0.42×10^{10}	0.38×10^{10}
	Lens of eye glasses	12	Na-24	0.63×10^{10}	0.59×10^{10}
	Frame of eye glasses	12	Au-198	1.07×10^{10}	
#23	Silver shield from film badge	~47	Cu-64	0.22×10^{10}	0.22×10^{10}
	Pencil clip	47	Mn-56	0.18×10^{10}	0.16×10^{10}
	Button	34	Cu-64	0.19×10^{10}	0.17×10^{10}
	Watch band	(86)	Mn-56	0.16×10^{10}	0.14×10^{10}

accident are their personnel dosimeters for the gamma rays and the whole body counts and blood activation for the neutrons. The activation of Na^{24} takes place throughout the body. The experiments performed to relate Na^{24} activation to neutron dose, however, have related the activation to the first collision dose. It has been customary to report first collision neutron doses in accidents such as the present one in the belief that greater complexity would hinder rather than help correlation of observed biological effects with physical dose measurements.

Employees #1 and #17 were close enough to the critical vessel that the actual absorbed dose must have been fairly non-uniform within their bodies. The relation of Na^{24} activation to first collision dose may not, therefore, be quite the same as in the calibration experiments. The relationship is even more complicated by the fact that we do not know the exact course of events following the first critical excursion. During this period the men were moving rapidly and their position and orientation relative to the critical vessel were constantly changing. We do not know if there were any other critical excursions during this period or whether they received practically all their dose during the first one. The only indication we have that these subsequent motions were not very important is the value of the ratio of the gamma ray to the neutron dose. This ratio was between 2 and 3 for the two men close to the critical vessel. This is in good agreement with values observed in similar circumstances.[6] Their motions and the possible later excursions would affect their personnel dosimeter readings even more than the Na^{24} activation because of the changing shielding of the dosimeters by the body. The fact that they do not appear to have had a substantial effect on the ratio suggests that most of the dose came during one critical excursion while they were nearly stationary.

The first collision doses determined from sulfur activation in hair were about one half those obtained from Na^{24} activation. They should, of course, be lower because they are the doses for only those neutrons above 2.5 MeV. The threshold detector, Table 1, would indicate that only 20 per cent of the dose should come from such neutrons. The application of the latter data are suspect because, as already discussed, the detector may not have been exposed to exactly the same spectrum as the people. On the other hand, some of the difference may be due to a difference in the relation between first collision dose and Na^{24} activation in the calibration experiments and in the present accident because of greater non-uniformity of the absorbed dose distribution during the accident. The neutrons/cm^2 detected by sulfur activation can also be compared with the number of thermal neutrons. There are several measurements of the two on exposed people that are for nearly the same parts of the body. A ratio of neutrons/cm^2 above the sulfur threshold to thermal neutrons/cm^2 of about 0.2 was obtained where such measurements were made. The threshold detector gave 0.3. Probably this is as close agreement as we can expect. The scattering and absorbing materials in a human body are enough different from those near the detector to produce this much difference in the thermal flux density. It appears that there may be some uncertainty in the neutron doses from the Na^{24} activation, but that it is probably not very great.

Employee #1 received the highest exposure. The neutron first collision dose was 23–30 rad. The exposure dose was 63 r at the surface in the central region of his body. The dose due to thermal neutrons was negligible in comparison. The P^{32} measurements in hair suggest a variation by a factor of at least 2 for the neutron first collision doses in different parts of the body. This is compatible with variation as the inverse square of the distance from the center of the critical vessel. The neutron dose to the eyes is considered to be of importance in an exposure such as this because of the possibility of cataract formation. Inverse square variation suggests a first collision dose of 42–54 rad from neutrons for his eyes.

Employee #17 received the next highest exposure which resulted in 9–12 rad from neutrons and 23 r in the central region of the body. These doses are related to those received by #1 by the inverse square of the distance from the center of the critical vessel. By the inverse square law the neutron dose to his eyes must have been 11–14 rad.

Employee #23 received about 3 rad from neutrons and 13 r and these must have been pretty uniform over his body. Employees #6 and #21 each received about 1 r and 0.34 and 0.16 rad from neutrons, respectively. The rest of the people in the 234–5 Building at the time of the accident received considerably less exposure. The doses they did receive can be taken to be those given by their personnel dosimeters (Table 2) and their whole body counts (Table 4).

REFERENCES

1. R. H. Wilson, *A Method for Immediate Detection of High Level Neutron Exposure by Measurement of Sodium-24 in Humans*, HW-73891 (1962).
2. G. S. Hurst, J. A. Harter, P. N. Hensley, W. A. Mills, M. Slater and P. W. Reinhardt, *Rev. Sci. Instrum.* **27,** 153 (1956).
3. J. A. Sayeg, D. G. Ott and P. S. Harris, *Dosimetry for the Little Eva Critical Assembly*, LA-2468 (1960).
4. G. S. Hurst, R. H. Ritchie and L. C. Emerson, *Health Phys.* **2,** 121 (1959).
5. G. S. Hurst, R. H. Ritchie, F. W. Sanders, P. W. Reinhardt, J. A. Auxier, E. B. Wagner, A. D. Callihan and K. Z. Morgan, *Health Phys.* **5,** 179 (1961).
6. R. H. Ritchie, H. B. Eldridge and V. E. Anderson, in *Selected Topics in Radiation Dosimetry*, pp. 651–666. International Atomic Energy Agency, Vienna, Austria (1961).
7. P. E. Bramson, *Calibration of the Hurst Neutron Threshold Dosimeter System at Hanford*, HW-66727 (1960).
8. D. J. Hughes, *Pile Neutron Research*, p. 139. Addison-Wesley, Cambridge, Massachusetts (1953).
9. R. H. Wilson, V. M. Milligan, C. M. Unruh and H. V. Larson, *Gamma Calibration and Evaluation Techniques for Hanford Beta-Gamma Film Badge Dosimeters*, HW-71702 (1960).
10. H. V. Larson and W. C. Roesch, *Gamma Dose Measurement with Hanford Film Badges*, HW-32516 (1954).
11. R. J. Smith, *Thermal and Fast Neutron Effects on Dosimeter Films*, NDL-TR-13 (1961).
12. F. Swanberg, *A Personnel Film Badge Neutron Dosimeter*, HW-56827 (1958).
13. I. B. Berlman, H. F. Lucas and H. A. May, *Rev. Sci. Instrum.* **24,** 396 (1953).
14. J. S. Reddie, *Determination of Film Exposure by Neutron Activation of the Reduced Silver*, HW-30606 (1954).
15. J. DePangher, L. L. Nichols and R. A. Kent, *Characteristics of a Large Neutron Moderator for Activation Studies*, HW-73913 (1962).
16. J. DePangher, R. A. Kent and L. L. Nichols, *Application of the Large Moderator to Dosimetry Studies of the Recuplex Incident*, HW-73914 (1962).
17. R. H. Wilson, and H. V. Larson, *Film Capabilities for High Level Dose Evaluation*, HW-71133 (1961).
18. W. C. Roesch, R. C. McCall and H. E. Palmer, *Hanford Whole Body Counter-1959 Activities*, HW-67045 (1960).
19. *Accidental Radiation Excursion at the Y-12 Plant*, Y-1234 (1958).
20. P. S. Harris, Acute Radiation Death Resulting From an Accidental Nuclear Excursion. Section VI Dosimetric Calculations, *J. Occup. Med.* Special Supplement, March (1961).
21. G. S. Hurst and R. H. Ritchie (Editor), *Radiation Accidents: Dosimetric Aspects of Neutron and Gamma-Ray Exposures*, ORNL-2748, Part A. (1959).
22. H. E. Palmer, *Radiology* **78,** 115 (1962).
23. R. W. Perkins, J. M. Nielsen and R. N. Diebel, *Rev. Sci. Instrum.* **31,** 1344 (1960).
24. Recommendations of the International Commission on Radiological Protection, *Brit. J. Radiol.* Supplement #6, 1955.
25. W. S. Spector, *Handbook of Biological Data.* Saunders, Philadelphia (1956).
26. W. H. Langham, Acute Radiation Death Resulting From an Accidental Nuclear Excursion. Section V. Special Studies, *J. Occup. Med.* Special Supplement, March (1961).
27. R. W. Perkins, *The Response of Various Detector Sample Arrangements for Gamma-Ray Spectrometric Measurements*, HW-68525 (1961).
28. W. B. Silker, *Analyt. Chem.* **28,** 1782 (1956).
29. D. F. Peterson, F. E. Mitchell and W. H. Langham, *Health Phys.* **6,** 1 (1961).
30. *Permissible Dose from External Sources of Ionizing Radiation*, NBS Handbook 59 (1954).
31. Personal communication, V. P. Bond to A. R. Keene, May 9 (1962).

Health Physics Pergamon Press 19

ACCURACY AND
OF G

EFFEC

RO
Department o
Uni

(*Receiv*

Abstract—Measurem
the effects of environm
irradiations of 1–4 hr
ranging from 1 hr to 1
½ hr to 1 week followin
decreases in gamma se
(80°F) as relative humi
to 49°C (120°F) produc
where sensitivity was i
and exposure conditio
exposures at very low
libration under high h
tivities during irradiat
The results indicate th
for short wearing inte
for these phenomena.

INTRODUC

Although many of the ph
influencing the response an
sensitive emulsions have be
very little work has been
effects of environmenta
humidity during irradiatio
latent image formation.

* Some of the material in t
at the Chicago meeting of the
14 June 1962. Work was s
with U.S. Public Health Se
logical Health.

† Fellow, Radiation He
Program, U.S. Public Hea
Radiological Health. Pres
Radiation Laboratory, U
Livermore, California.