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JUL 16 1965

CONF-650302-21

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THE HANFORD CRITICALITY ACCIDENT:
DOSIMETRY TECHNIQUES, INTERPRETATIONS AND PROBLEMS

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1. Introduction

A criticality accident occurred in a building where there were 22 employees on April 7, 1962 at the U. S. Atomic Energy Commission's Hanford Plant, located in the State of Washington. In contrast to several earlier criticality events at other locations in the U. S. where personnel dosimetry measurements were not available, especially in respect to personal film dosimetry, all of these employees were wearing film dosimeters. An official report^[1] of the dosimetry investigation, which essentially covers the period from eight hours to several weeks post incident, has been published. Where appropriate, pertinent condensations of the findings are included here. This paper describes the hitherto unreported events, uncertainties, and most important, the lessons we learned from this actual test of our emergency procedures. It also centers around the results of the particularly comprehensive evaluations conducted upon the three persons that received the highest doses.

2. Description of the Accident

The criticality occurred at a plutonium waste recovery facility in a nongeometrically safe solution transfer vessel. The characteristic Cerenkov radiation was observed by the three employees in the room, one of whom was standing within 10 feet of the vessel. The evacuation horns sounded immediately, and these three employees, together with 19 other employees from other parts of the building, evacuated the building promptly according to established procedures.

Two recording BF_3 neutron counters (one for high, one for low levels) were operating in another building nearby at the time of the accident. They indicated an initial excursion the exact magnitude of which cannot be determined because the reading, which was recorded only every 30 seconds, was off-scale.

It may be expected that these readings could vary by orders of magnitude within such a time. After the initial pulse, a continuing nuclear reaction was of sufficient magnitude to keep the recorder off-scale for a period of 30 minutes. After the recorder returned to on-scale readings, the fissioning continued at a generally reduced rate until 36 hours after the incident began. It appears that the three employees in the room where the accident occurred left the room so promptly (in a matter of seconds) that they were exposed only to the initial pulse.

The 22 personnel present in the building at the time of the accident were moved to a first aid station in the immediate area where contamination surveys were made and dosimeters were collected. None of the employees was contaminated. All involved were wearing film badge dosimeters and, in addition, several were wearing film finger rings.

An emergency procedure, "quick-sort", had been developed^[2] for use in a criticality event to detect high level neutron exposure in the field by direct survey of the human body with a simple GM-type portable radiation survey instrument held against the stomach and abdomen area. A general relationship between body weight, count rate and dose had been developed and expected to provide a reasonable estimate of a neutron dose received from a criticality accident. The general relationship was:

$$D = 2.5 \text{ R/M}$$

R = Count rate in c/m for a GM tube¹ instrument calibrated
to indicate 3,200 $\frac{\text{c/m}}{\text{mR/hr}}$ with a radium radiation source.

M = Body weight in pounds.

D = Dose in rads.

¹Wall thickness 35 mg/cm² (Type 1B85)

Similar count rates may also be obtained by positioning the probe under the arm and flat against the side of the chest.

2.1 First Dose Estimates

On arrival at the hospital, the three individuals were again carefully monitored and found free of contamination. The "quick-sort" procedure was repeated with essentially the same results and are presented in Table I.

All personnel assigned to the facility in which the accident occurred were thoroughly trained, and therefore, were well aware of the consequences of being exposed at short distances to a critical event. Understandably, employees numbers 1 and 17 were in a state of anxiety, employee number 1 having no doubts that he had received a fatal dose.

Although the "quick-sort" measurements indicated that the neutron doses were only about 32, 7, and 4 rads, radiation protection personnel had limited confidence in these preliminary estimates for three reasons: the procedure had never before been tested in practice; the estimated doses were much lower than one would expect, based on the reported distances from the source of the radiation; and the magnitude of the error introduced by differences between the calibration and exposure neutron energy spectra was unknown. Table II compares the results of the whole body counter with the "quick-sort" procedure estimates.

In spite of the fact that no corrections were made for differences in neutron energy spectra, the "quick-sort" procedure can be seen to have quickly provided what proved to be remarkably valid estimates of the neutron doses which had been received. It should be pointed out that dosimetry results obtained from analysis of blood sodium activation, whole body counting, and film badge readings all stemmed from different personnel in various laboratories,

hence the data are free of the bias which could be injected by one group making all the interpretations.

Hanford Film Badge Dosimeters, worn by all persons present in the building where the critical event occurred, were promptly collected for special processing. All dosimeters were surveyed for contamination before they were permitted in the processing building. The dosimeter in use at that time consisted of a film packet, containing duPont 508 (sensitive) and 1290 (insensitive) film, behind aluminum and silver absorbers and an "open window". A strip of lead tape, perforated with the payroll number, lay along one edge of the film, and was normally used for film identification by local x-ray exposure coding.

The probability of excessive film darkening resulting from the exposure received during the accident caused us to alter the usual method of identifying film by x-ray coding. A pinhole coding was perforated through the film packet and film then covered with light opaque tape to assure light integrity prior to processing. A commercially available perforator, modified to suit our particular identification needs, was used. Additionally, the film wrappers were identified and filed in the same order as that of the processed film. Subsequently, the wrapper markings were matched with the perforated film for further assurance of proper identification.

Gamma calibration films (10, 25, 35, 50, 60, 70, 120, 150, 300, 450, 600, and 1200 R) are kept readily available for emergency use at all times, and a set was processed with the personnel exposure film. Because of excessive darkening of the sensitive film, dose evaluations were made using the insensitive (1290) film.

The first estimates of gamma dose for the three involved employees were made 3-1/2 hours after the accident by visual comparison of their badge films

with calibration films. The first estimates reported were 67, 30 and 10 R. Incidentally, the estimate of 67 R was arrived at by noting that the film density was about two-thirds of the way between the densities of the 60 and 70 R calibration films. Although these low gamma exposure estimates tended to confirm the low neutron dose estimates, and together indicated that no fatal or severe exposures had been received, we delayed announcing an estimate until 4-1/2 hours after the accident, when the final dose estimates from the 1290 film (densitometer rather than visual readings) and blood sodium activation measurements were available. These results are presented in Table III. These estimates were passed on to medical personnel and to the employees involved, but were not believed by employee number 1. It was necessary for radiation protection personnel to discuss his exposure in detail and repeatedly reassure him of his estimated dose before we were able to convince him that he had not been fatally exposed.

3. Discussion and Problems

3.1 Film Badge Dosimetry

Although gamma calibration films in the required ranges were available and were processed with the personnel exposure film, the areas under the aluminum and silver absorbers, because of slow neutron activation, were additionally darkened and the film exposure could not be evaluated in the usual manner. The exposure was interpreted from the densities under the unshielded portion of the dosimeter (the open window). This naturally introduced some uncertainties as the exposure could be as much as 15 percent too low because of the lack of electronic equilibrium and differing photon spectra.

The area underneath the small piece of lead tape used for identification purposes was used to compare with the area under the unshielded portion. The

readings were compared with similar readings on the calibration film and they gave dose estimates that confirmed those from the open window readings if one assumed that there was no appreciable slow neutron activation of the lead tapes and no appreciable effect due to the degradation of the photon spectrum. Another item which became of immediate concern was the darkening of the film due to neutron activation of the materials in the emulsion. For the spectrum from this criticality event, 7 percent of the dose measured was attributed to this darkening. The values in rads of thermal or fast neutrons that produce the same darkening on the film as one Roentgen of cobalt 60 gamma rays were taken from the work of R. J. Smith.^[3]

Even though it was realized that the film and ring badges of the exposed personnel could give results that were in error by factors of three or four due only to differences in attenuation between what the body and badge received, it was found in this event that primary reliance for dose evaluations could still be placed on film data interpretations. The inherent limitations of our film badges, which at that time included only film, became clearly evident. The desirability of extending the range of gamma dose measurements and the inclusion of capabilities for measuring neutron flux and spectra following a criticality event were noted. Our new film badge is responsive to these needs and although the details of the construction and the performance characteristics have been reported,^[4] the most essential capabilities and inclusions adopted for this type of monitoring are noteworthy.

For instance, the inclusion of silver phosphate glass fluorod dosimeters has extended our gamma dose measurement capability to 10,000 R, as compared with the 1500 R limit of the old dosimeter. The fluorods are incorporated into the film dosimeter in such a way as to be conveniently accessible and yet

relatively free from contamination problems. For improved energy response, one fluorod is placed within a tantalum sleeve. A set of foils consisting of indium, cadmium, copper and sulphur provides a capability for measurement of neutron spectra and dose up to 2000 rads. Because of the activity induced by neutrons on the indium foil, persons grossly exposed to neutrons may be segregated by measuring the activity of the foil while still in the badge, using the GM counter.

3.2 Blood

The initial blood samples from these employees were obtained at a first aid facility near the site of the accident, within 30 minutes. However, the samples were only about 2 cc each and the evaluators became concerned regarding the accuracy of the volume determinations since some coagulation occurred before the measurements could take place. A second set of samples, to which Heparin was added to prevent coagulation, was taken at the hospital two hours after the accident. The results^[5] from both sets of samples, using the modified procedure for the second set, are shown in Table IV.

It has been recommended^[6] that if the dose is believed to be more than 100 rads of neutrons, the volume of the blood sample should be about 10 cc; however, if the dose is less than 10 rads, the volume should be 100 cc. Advantages of evaluating sodium activation from the blood serum, rather than from the whole blood are that one is freed from adding anticoagulants to the blood and the sample volume may be more precisely measured. With the latter technique the sample is allowed to clot and the volume is measured after centrifuging the solid portions of the blood from the serum.

It is expected that in cases of high exposures, the subjects may be in a state of shock, requiring the administration of intravenous solutions containing sodium; therefore, for simplicity of future calculations, blood samples should be obtained before the administration of the salt solutions. In using blood

sodium activation for a measurement of the fast neutron dose, it should be noted that mixing of blood gives an average value for exposure of the whole body, and under conditions of partial body shielding or gross asymmetry of the radiation field, results may be of limited biological significance.

3.3 Contamination

Fortunately, no contamination was released in this accident. Personnel contamination, if not promptly and easily removable, would perhaps have delayed or entirely voided the estimation of neutron dose by the "quick-sort" method, beyond the point of usefulness. However, in accidents where contamination of personnel does not result, such a procedure, although crude, can be counted on to provide satisfactory preliminary estimates of neutron dose which are of particular value because of the promptness of the results. In accidents where contamination of personnel has occurred, first estimates of neutron dose would probably be obtained by blood sodium activation analysis.

3.4 Whole Body Counting

The whole body counter was in stand-by readiness within two hours after the accident; however, counting of the involved personnel was not begun until 6-1/2 hours after the accident. Medical procedures and observations were properly taking precedence. The collection of information on whole body sodium-24 neutron dosimetry took several hours, and it quickly became evident that the sodium content of man is not as well established as would be desired. In spite of uncertainties in spectrum and body sodium content, the neutron dose of employee number 1 was estimated by whole body counting at 8 hours post accident to be 24 ± 6 rads, again in remarkable agreement with blood sodium measurements.

Whole body counting for the determination of absorbed dose would be greatly complicated by external body contamination. The contamination could be such as to so seriously interfere with the counting procedures as to prohibit valid measurements. On the other hand, the employee could be contaminated, for instance, with plutonium which would not interfere substantially with the sodium-24 count but which could contaminate the counting facilities to a serious degree.

3.5 Excreta

It was not possible to use the data from the analyses of excreta to confirm the estimations of exposure doses obtained by the other methods. The sodium-24 in urine was not found to be directly proportional to the body burden in these exposed employees.^[5] Two employees, one receiving twice the dose of the other, excreted in their urine approximately the same amount of sodium-24 over a 6 day period. Additionally, it was found that the urinary rate of sodium-24 excretion was not a constant function of the body burden. The variations ranged from 4 to 11 percent of their body burdens during the first full day following the exposure and were certainly related, at least in part, to our inability to relate the urinary excretions to the metabolic periods which they represented.

The daily fecal excretion rate of sodium-24 ranged from less than 1 to about 7 percent of that present in the urine. In addition to the sodium-24 detected in the feces, trace amounts of chromium-51, zinc-65, zirconium-niobium-95 and ruthenium-103-106 were also detected. Zinc-65 and chromium-51 are common in people that live near Hanford because of the presence of these nuclides in the Columbia River and it is probable that they were ingested earlier with food or drinking water.^[7] The zirconium-niobium and ruthenium had probably been ingested from fallout.

3.6 Hair

The neutron doses to localized areas and to critical organs of the employees' bodies were estimated by determining the phosphorus-32 activity in hair sampled from selected portions of the body, together with a knowledge of the approximate neutron spectrum. Since activation in hair is a reaction at the body surface, its greatest value is in estimating personnel orientation and localized dose, especially where the radiation has not been severely degraded and where there is considerable nonuniformity of dose distribution.

In this particular incident, we used one gram samples of hair from various areas of the body for the estimation of the dose of neutrons of energies in excess of 2.5 Mev and the agreement with other methods of estimating the neutron dose was quite good. For instance, for employee number 1, this technique gave a first collision rad dose of 9.2 for the head, 10.5 for the chest, 6.8 for the pubic area, and 5.2 for the legs. While this method is in obvious contrast to the fast neutron average whole body doses obtainable through blood activation analysis, for comparison purposes only, one may assign an "average" whole body dose of about 7-1/2 rads to this employee due to neutrons above 2.5 Mev. Since this accounted for about 25 percent of the neutron dose, this method estimated the neutron dose at 30 rads, compared with about 25 rads obtained using the whole body counting or blood sodium data. See Table V.

Although our emergency dosimetry procedures specified the collection of 1 gram of hair, it was not until we tried collecting them did we fully realize what a substantial quantity 1 gram of hair really is. Employee number 1, receiving the highest dose, was particularly devoid of hair and the collection of adequate amounts from areas of interest was difficult. Another difficulty which could arise in the phosphorus-32 analysis of the sulphur activation in the hair is contamination; however, it is expected that some areas of the body

could be found to be relatively well protected. In our case, phosphorus-32 analysis provided reassuring support to our other interpretations.

3.7 Other Materials

In order to provide support for the estimates of the applicable neutron spectrum at or in the immediate location of the exposed employee, it was found desirable to make neutron activation analyses of certain materials such as aluminum, copper and gold. These came from the personal effects of the exposed subjects, scrap materials and tools. One difficulty with the use of objects not being carried on individuals is re-establishing the exact location from which the objects were recovered. As for the personal items, we found all of the following useful: coins, jewelry, belt buckles, metal buttons, pens and automatic pencils, cigarette lighters and cases, wrist watches and metal from spectacle rims.

3.8 Dose Equivalent

As noted throughout the paper, reference has been made to "first collision neutron dose". The reason is that this was the data that was available at that time. On the one hand it is realized that this expression is no longer in recommended use; however, on the other hand, no good substitute has been proposed. To further compound our difficulties, we found to attempt a prediction of the consequences of radiation doses from criticality accidents is fraught with uncertainty. Among these uncertainties are dose rate and its effect, whether the exposure was from a single burst or from multiple bursts, application of spectrum data and a reliable index of biological damage. The unidirectional nature of acute exposures leads to severe problems in attempting to apply an RBE, as the exposure will most likely be nonuniform within the tissues of interest. Additionally, the heterogeneous energy spectrum of the incident radiations must

have produced a very nonuniform distribution of dosage in depth, particularly where the spectrum included large, low energy components.

It thus became extremely difficult to postulate the degree of probable biological insult. The exposure dose in air must have varied from 2 to 20 times greater than the midline tissue dose.^[8] The use of the midline dose, or other measures, such as exit dose or gamma-roentgen dose, was not attempted for obtaining a definition of exposure level. There is evidence, however, to support the hypothesis that the biologically effective dose is best defined as the average dose to the bone marrow for both acute and chronic measures of injury^[9] but to obtain such data would be quite complicated.

It was recognized that under our high dose and dose rate conditions, the accepted quality factor values normally used for radiation protection purposes did not apply even though the personnel were probably somewhat uniformly irradiated. Dog data^[10] indicate that the RBE for mortality may not be a sensitive function of neutron energy in large species. The report suggests a value of one as reasonable for bone marrow failure and a value of two for intestinal injury and its associated mortality. The conventional use of the rem is obviously inapplicable. Even today, some three years following the incident, we are still concerned as to the best and most appropriate method of expressing the doses received.

3.9 Dosage Calculations and Factors

Although the dosimetry preplanning for an incident of this magnitude was satisfactory, it emphasized the necessity of maintaining up-to-date agreed upon factors and procedures, together with notes as to limits of applicability, for estimating high level radiation doses. At the time we had formal detailed procedures for most techniques used but did not have procedures for body

sodium activation measurements using whole body counting and phosphorus-32 in hair measurements.

Sodium-24 activity ingested from activated Hanford drinking water was routinely measured in vivo, using the Hanford Whole Body Counter. Therefore, no special calibrations of the whole body counter for sodium-24 activity were needed to measure the personnel involved in the incident. However, routine measurements were normally converted to a percentage of a maximum permissible body burden, and not to neutron dose. A copy of the dosimetry summary of the last criticality incident at Los Alamos was consulted and found to contain both the Oak Ridge^[11] and the Los Alamos^[12] dose conversion factors. These two experimentally derived factors were averaged and the resulting factor of 215 rad-kG/ μ C was used to estimate the neutron dose. This factor assumed that each man's sodium concentration was the same as the standard man^[13] (1.5g/kg) and that standard man was the same as the burro used in the Oak Ridge experiment.

In contrast, the detailed procedures for estimating neutron doses to the blood from fission spectrum neutrons had been established and included in formal procedures. This accounted for the rapidity with which blood analysis was accomplished. The conversion factor of 0.29 μ Ci/cm³ came from the Oak Ridge Burro experiment where the burro received 48 rads (1.65×10^5 rad-cm³/ μ C). This factor assumed that the sodium concentration in whole blood and blood serum of the exposed subjects was about the same as in the burro. Whole blood and blood serum sodium concentration measurements were not made on our personnel; however, current emergency procedures now call for such measurements to be made.

Although no formal detailed procedure was available for phosphorus-32 in hair measurements, the analytical chemistry and dosimetry evaluation techniques had been published in the literature^[14] by Petersen, et al, the preceding

August. We used their formula, which gave factors of 6.55×10^6 neutrons/cm² per dis/min-g sulphur and 0.0246 rads per dis/min-g sulphur. The sulphur content of the hair was found to be in reasonable agreement with their value of 47.7 mg sulphur/gm of hair and was used in all calculations.

3.10 Medical Treatment

The complete medical findings, treatment and observations have been reported in detail.^[15] No problems regarding such important factors as availability of physicians, hospital admittance, possible contamination or adverse reactions of personnel arose. The plant had its own physicians who were also on the staff of the local hospital. Nevertheless, one could see how it would be possible to worsen a grave situation in the event that attending medical personnel are not conversant with the problem and, because of the lack of this knowledge, create unnecessary and unwarranted problems.

Although the staffs of local hospitals often may not be well versed in the handling of radiation accident cases, there generally is a radiologist in the vicinity who does have valuable experience in this area. Additionally, support can be obtained from personnel working in hospital radioisotope laboratories. It would therefore be important for each installation where accidental radiation exposures are a possibility to have a clear-cut plan of action for the handling of accident cases worked out beforehand, particularly if there is a possibility of radioactive contamination.

4. Conclusion

Normal and alternate procedures should be designed around the primary purposes of emergency dosimetry; these being to (1) segregate as rapidly and as knowledgeably as possible those personnel most likely to have suffered

varying degrees of excessive radiation exposure, and (2) provide physicians with timely and useful exposure data.

We accomplished the first task of segregation and identification quite well but did not accomplish the second task of furnishing data to the physicians as rapidly as possible. By the time we reported our results, 4-1/2 hours after the accident, the clinical manifestations had established for the doctor, patient, and next of kin that fatal doses had not been received. We can and should shorten this torturous delay. Had we had more experience with and confidence in our emergency procedures, we could have reduced the time substantially. We just were reluctant to believe the doses were so low to personnel that were so close to the event. Today, as a result of the experience we gained, we have the confidence to predict quickly the doses received and to rely on the results. We have assigned the following order to our procedures: (1) "quick-sort" sodium-24 procedures, (2) film badges, (3) blood or blood serum sodium-24 activation analysis or whole body counting, and (4) phosphorus-32 activation in hair. The other procedures to enhance the accuracy of the dosimetry to help in later scientific understanding of the observations made are relegated to more subordinate positions.

Finally, in our experience, even with a large and competent staff available to handle the situation, backup support in the nature of consultations with various experts was still desired. This may quite well have been more in the area of moral support, but nonetheless, was deemed necessary. It was especially useful to have a prepared list of readily available specialists in the area of dosimetry and medical treatment.

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TABLE I

"QUICK-SORT" PROCEDURE ESTIMATES

<u>Employee</u>	<u>Body Weight pounds</u>	<u>Observed Counts/Minute^a</u>	<u>"Quick-Sort" Dose Estimates, rads</u>	<u>Employees' Estimates, Distance from Source^b</u>
1	155	2000	32	3-4 feet
17	216	600	7	7-9 feet
23	188	300	4	25 feet

^aBackground activity negligible.

^bLater measurements showed that the actual distances were somewhat greater than those indicated above.

TABLE II

COMPARISON OF "QUICK-SORT" ESTIMATE AND
WHOLE BODY COUNTER EVALUATION OF NEUTRON DOSE

<u>Employee</u>	<u>Whole Body Counter Dose Estimate, rads</u>	<u>Distance From Critical Event</u>	<u>"Quick-Sort" Dose Estimate, rads</u>
1	24	6-8 feet	32
17	9	10-11 feet	7
23	≈3	≈26 feet	4

TABLE III

DOSE ESTIMATES^a 4-1/2 HOURS POST INCIDENT

<u>Employee</u>	<u>Gamma Exposure (R) From 1290 Film in Hanford Film Badge Dosimeter</u>	<u>Neutron Dose From Blood Sodium Measurements, rads</u>
1	63 <u>+10%</u>	25 <u>+10%</u>
17	23 <u>+30%</u>	15 <u>+15%</u>
23	13 <u>+15%</u>	4 <u>+30%</u>

^aFinal gamma dose estimates were the same and the final neutron exposures were: employee #1, 23-30 rads; employee #17, 9-12 rads; employee #23, approximately 3 rads.

TABLE IV

SODIUM-24 IN BLOOD

<u>Employee</u>	<u>Sample Volume cm³</u>	<u>Na²⁴ (μCi/cm³ blood)</u>	<u>Neutron First Collision Dose, rads</u>
1	2	1.5 x 10 ⁻⁴	25 <u>+2.5</u>
1	10	1.8 x 10 ⁻⁴	30 <u>+3.0</u>
17	2	8.8 x 10 ⁻⁵	15 <u>+2.2</u>
17	10	7.3 x 10 ⁻⁵	12 <u>+1.2</u>
23	2	2.0 x 10 ⁻⁵	4.0 <u>+1.2</u>
23	10	2.1 x 10 ⁻⁵	3.4 <u>+0.8</u>

TABLE V

SUMMARY OF FIRST COLLISION NEUTRON DOSE ESTIMATES^[5]

<u>Employee</u>	<u>Whole Body Sodium-24</u>	<u>Blood Sodium-24 (Ave.)</u>	<u>Phosphorus-32 in Hair^a</u>
1	24	27	30
17	9	13	14
23	3	3	5

^aValues assume 25% of the first collision neutron dose was due to neutrons of energy greater than the $S^{32}(n,p)P^{32}$ threshold of 2.5 Mev.