REPOSITORY DOE-FORRESTAL
COLLECTION MARKEY FILES
BOX No. 3 OF 6
FOLDER CRITICALITY MACHINE SOURCE ACCIDENTS

Reprinted from JOURNAL OF OCCUPATIONAL MEDICINE
Vol. 7, No. 3, March 1965
Copyright © by Industrial Medical Association
HOEBER MEDICAL DIVISION OF HARPER & ROW, PUBLISHERS
Printed in U.S.A.

704638

Journal of Occupational Medicine

Biologic Effects of Human Radiation Exposure

Report of a Criticality Accident

P. A. FUQUA, M.D., W. D. NORWOOD, M.D., and S. MARKS, M.D., Richland, Wash.

A CRITICALITY ACCIDENT occurred in a plutonium waste, chemical recovery facility at the Hanford Atomic Products Operation, Richland, Wash., on Apr. 7, 1962. Three healthy workers in the facility were exposed to a wide range of non-uniformly distributed doses of mixed radiation. This report endeavors to summarize the biologic effects observed over a 2-year period in these employees and pertinent information relating their exposures to the observed effects. Extreme care was given the study of gonadal effects because of the great sensitivity of these organs, the paucity of available relevant data, and medicolegal implications. The availability of talented teams of scientists, equipped to operate quickly in a wide range of disciplines, made this study possible. Many people participated in various phases of the study, and detailed accounts of particular portions have been prepared; some have been reported elsewhere.[1-5]

All employees were wearing dosimeters when the nuclear excursion occurred. The data supplied by the fixed and personnel dosimeters were supplemented by information obtained by ingenious techniques developed in connection with previous accidents elsewhere.[6-9] Since early vomiting, diarrhea, and prostration were absent, it was possible quickly to reassure the patients that they had not sustained a critical exposure.[10-12] Attention could then be turned to the scientific aspects of the study.[13-18]

Description of the Accident

The accident, involving a sudden release of neutrons and gamma radiation, occurred when an addition of plutonium-bearing waste liquid to a small tank caused the critical amount to be exceeded. The nuclear excursion was the first to have occurred in any production facility during 20 years of operation at Hanford. There were 22 employees in the building, at variable distances from the small tank at the time the critical excursion occurred. The criticality alarm siren sounded at once, and all persons quickly evacuated to a nearby gatehouse. Within a few minutes they were taken by bus to the nearest area medical facility. Those employees who had been close enough to observe the Cerenkov radiation flash were examined quickly with a Geiger counter held at their abdomens while they bent over the counter.[19] This was done to determine which employees had been exposed

From the Occupational Medical Operation, Hanford Atomic Products Operation, Richland, Wash., operated by General Electric Company for the U. S. Atomic Energy Commission.

1005473

to significant fast neutron doses. Soon all were so checked, and it was established that only a few nearest the critical tank had sustained significant neutron doses as indicated by the gamma dose from the activated sodium in their bodies.

Information was obtained immediately from each employee to establish where he had been when the criticality alarm sounded and by what route he left the building. All were quickly surveyed for surface contamination with radioactive material; none was found. Personal effects were examined for radioactivity and then submitted for laboratory study. Blood samples were collected for determination of the content of radioactive sodium (Na^{24}). Hair samples were collected for determination of neutron activation of sulfur to phosphorus. Urine samples were collected for the assay of radioactivity, and preliminary medical examinations were made. The 3 employees determined to have the highest exposure were hospitalized for further examination and observation. All others received exposures estimated to be no more than 2 rems. Within a few hours the 3 employees were sent to the Hanford whole-body counter for examination. During the following 2 days, all other evacuees from the building were examined at the whole-body counter.

Observations

Dosimetry

The dosimetry investigations were conducted by members of an investigation committee who interpreted and reported their findings in detail.[1] The findings are summarized as follows.

The positions of the 3 employees at the time of the initial excursion were carefully determined (Fig. 1). Employee 1 was manipulating a valve at the face of the hood containing the tank. His eyes were about 5 feet from the center of the critical tank, K9; the parts of the trunk of his body were between 6 and 8 feet away. Employee 2 was standing about 2 feet to the side and about 5 feet behind Employee 1. Employee 3 was about 26 feet away. Employees 1 and 3 were wearing film ring dosimeters, and all 3 wore Hanford film badge dosimeters.[20] Because of the extent of the exposure, the insensitive (1290) film from their dosimeters was used to obtain their doses. This was the primary source of data for determining the gamma ray dose. Since back-scattering for gamma rays is small, the dosimeters indicate the first-collision photon dose at the place they were worn. The experiments performed to compare Na^{23} activation with neutron dose have related the activation to the first-collision dose. It has been customary to report first-collision doses in accidents such as the present one in the belief that greater complexity would hinder rather than help correlation of observed biologic effects with physical-dose measurements. Employees 1 and 2 were close enough to the critical vessel that the absorbed dose must have been fairly non-uniform within their bodies. The relation of Na^{23} activation to the first collision dose may not, therefore, be quite the same as in calibration experiments. The relationship is complicated by movement of the men following the first critical excursion. There is an indication that subsequent movements were not important since the value of the ratio of the gamma ray to the neutron dose was between 2 and 3 for the 2 men closest to the critical vessel. This is in good agreement with values observed in similar circumstances. The fact that motions and later excursions do not appear to have a substantial effect on the ratio suggests that most of the dose came during 1 critical excursion while the men were nearly stationary. The gamma whole body exposure dose was reported as that at the body surface in the central region of the body.

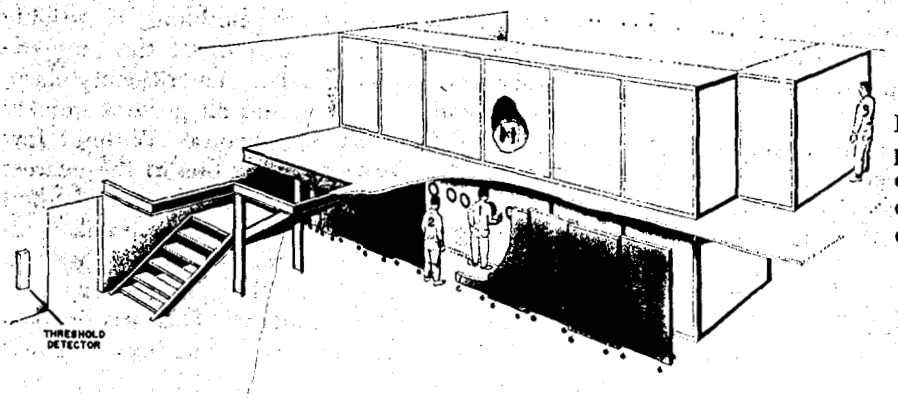

Fig. 1. Positions of Employees 1, 2, and 3 in Recuplex area at time of accident. Position of threshold dosimeter is also shown.

1005474

In dose determinations, reliance was placed mainly on personnel meters for the gamma rays and on whole-body counts and blood-activation measurements for the neutrons. Further information was obtained from measurements of P^{32} in hair and of radioactivity in objects on the exposed persons and from threshold detectors and recording instruments in the building. The estimated accuracy was considered to be satisfactory and offered a good opportunity to study the effects of such doses in normal humans.

The whole-body, eye, and gonad dose ranges in the 3 cases have been carefully defined according to the gamma ray roentgen and neutron rad content and multiplied by effectiveness factors to convert to rems[21, 22] (Table 1). The effectiveness factor includes other factors in addition to relative biologic effectiveness (R.B.E.). In this study the effectiveness factor is taken to be the product of (1) quality factor (R.B.E.), (2) partial body factor, and (3) penetration factor. The effectiveness factor of a rad of neutrons to a rad of X or gamma radiation in producing gonadal damage is not well known in humans, and investigations to better determine this factor have been started at this project. The figure of 10 which we have used is merely our best guess. Rapidly administered gamma radiation is more effective than slowly administered gamma radiation in producing death from bone marrow failure. This effectiveness factor of gamma radiation under such conditions would probably be 2 or more. However, we have not applied this factor since it has not been done in the past, and more knowledge is needed to make this a reasonably accurate figure. The quality factor which is synonymous with R.B.E. for fast neutrons in dogs has been closer to 1 than 2 for mortality related to bone-marrow failure, under conditions approximating uniform exposure.[23–25] However, this is offset in the present instance by the fact that the neutron dose is taken as the single collision dose which, for Employee 1 is some 50% lower than the multiple-collision absorbed dose.[5]

Clinical Course and Management

Employee 1 With only the knowledge that a criticality reaction had occurred about 1 hr. previously in this employee's immediate work location, he was examined in the hospital emergency room. He was a white male, age 40, with 3 children and a pregnant wife. The employee was obviously apprehensive; he believed that he had probably received a fatal exposure. His apprehension was controlled, but he demanded that he be told all the facts just as soon as they were known. He described seeing a flash and experiencing a momentary sensation of heat over his trunk. He experienced no nausea, pain, or any other specific complaints. Physical examination revealed no findings that might be related to a radiation exposure. He was admitted, however, to a single room in the hospital for observation, specimen collection, and study. The employee complained of a dry mouth and a heavy, tense feeling in his abdomen for several hours, during which he repeatedly sipped water. As time passed and no nausea, vomiting, or prostration appeared, we were able to assure him that his exposure was not critical. His apprehension was further relieved when he was advised

TABLE 1. WHOLE-BODY, EYE, AND GONAD DOSE RANGES IN 3 EMPLOYEES

Region	*Gamma (r)*	*Neutrons (rads)*	*Effectiveness factor for neutrons*	*Effectiveness factor for gamma radiation*	*Rems**
EMPLOYEE 1					
Whole body	63	23–30	2	1	109–123
Eyes	90	42–54	7	1	384–468
Gonads	28	19–24	10	1	218–268
EMPLOYEE 2					
Whole body	23	9–12	2	1	41–47
Eyes	28	11–14	7	1	105–126
Gonads	17	8–10	10	1	97–127
EMPLOYEE 3					
Whole body	13	3	2	1	19
Eyes	13	3	7	1	34
Gonads	13	3	10	1	43

*Rems for whole body marrow failure are calculated, for example in Employee 1, as follows: Rems = (63 × 1) + (23 or 30 × 2) = 109–123.

1005475

of the estimated magnitude of his exposure about 5 hr. after the accident. About 24 hr. after the accident the oral temperature was 100°F. The fluid intake was above normal for several days. On the third day activation of a chronic eczema on the dorsum of the fingers of his right hand occurred. A palpable and tender epitrochlear node was also present at this time. It was felt that the eczema with secondary infection would account for the fever. These manifestations subsided in about 36 hr. The employee vomited once after breakfast on the seventh day. On the fourth, seventh, and eighth days, periods of leave from the hospital were granted between the hours of 1:00 and 9:00 P.M. He was discharged on the ninth day.

Employee 2 This white male employee, age 50, with 4 children, also saw the flash, but because of the promptness of the warning signal and his position in the workroom at the time of the criticality, he did not believe that he had sustained a serious exposure. He demonstrated no apprehension during the course of an examination in the emergency room. The examination revealed no findings which could be related to a radiation exposure. He was admitted to a single room in the hospital for the reasons mentioned for Employee 1. On the second day he experienced a mild shocklike reaction which he described as a sudden feeling of weakness. There was no associated pain, and he recovered rather quickly. On the fifth day a testicular biopsy procedure was scheduled but was not carried out because of a hypotensive reaction during the period of surgical preparation. His periods of leave and discharge from the hospital were the same as for Employee 1.

Employee 3 This white male employee, of dark complexion, age 27, and single, was farther from the criticality vessel than were Employees 1 and 2. He was examined and admitted to the hospital. The employee had no relevant complaints initially or during hospitalization, and the examination revealed no findings referable to radiation exposure. On the evening of the fourth day, he developed an erythema on his face that was attributed to sun-and-wind exposure the preceding afternoon. His hospitalization was otherwise uneventful. His leaves and discharge from the hospital were the same as for Employees 1 and 2.

Gonadal Study

In order to assess the effects on gonadal function, the following studies were carried out: (1) testicular histology; (2) seminal fluid examination[20]; (3) urinary gonadotrophin excretion (general gonadotrophin and luteinizing hormone) assays; and (4) urinary estrogen excretion. These studies have been reported elsewhere[5] and the findings are summarized as follows:

Histology Employee 1 (dose 218–268 rems) sustained damage to spermatogenesis. Microscopic examination revealed a varied pattern of damage. Some of the seminiferous tubules were devoid of germinal epithelium and were populated by Sertoli cells only. Others showed a minimal to moderate reduction in germinal cells, whereas additional tubules demonstrated essentially normal spermatogenesis. The tubular membranes showed little sclerosis and hyalinization, even in those tubules containing no germinal epithelium. Leydig cells were considered normal in all respects (Fig. 2). The microscopic examination in Employee 2 (dose 97–127 rems) revealed minor deviations from normal, but it was not possible to relate these changes to irradiation exposure. Employee 3 (dose 43 rems) revealed a normal histologic pattern and sperm count.

Seminal Fluid, and Gonadotrophin and Estrogen Excretion Serial sperm counts in Employee 1 showed a significant reduction 9 weeks after the accident, and reached a low of 0–2

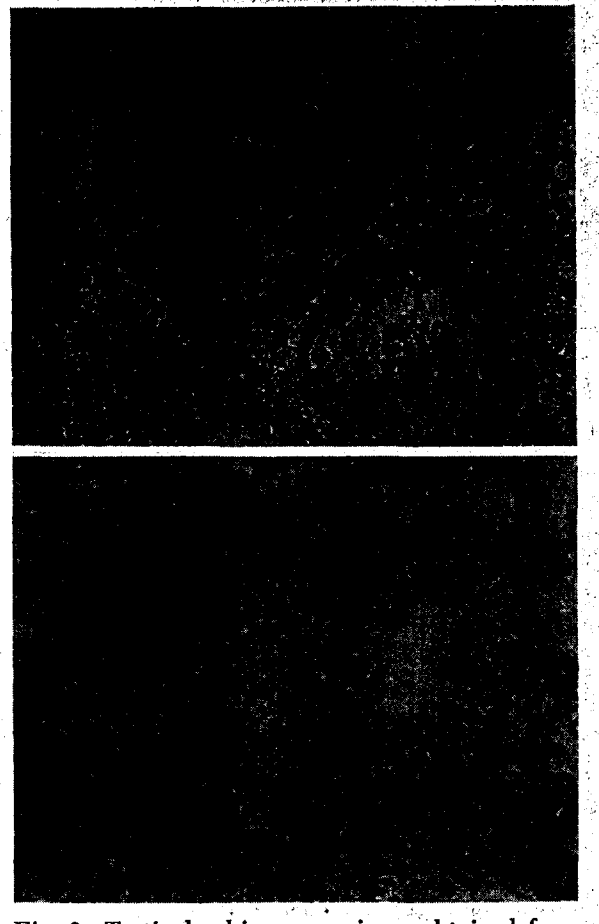

Fig. 2. Testicular biopsy specimen obtained from Employee 1, 8 months after radiation exposure. Degree of damage varies. Some tubules contain all germinal elements whereas most severely damaged lack germinal cells. Latter tubules are populated by Sertoli cells. Tubular membrane fibrosis is minimal in some areas and nonexistent in others. Although not shown here, Leydig cells appeared normal.

1005476

spermatozoa per high-power field by the twenty-seventh week. Thereafter the sperm counts increased and were virtually normal by 46–49 weeks after the accident. Serial determinations of urinary gonadotrophin excretion were made in each case. A general or total gonadotrophin assay which measures follicle-stimulating hormone (FSH) and luteinizing hormone (LH) was carried out in each instance. At various intervals LH assays were performed. The general urinary gonadotrophin titers for Employees 1 and 2 were normal initially but increased to pathologic levels by the eighteenth week in Employee 1 and by the seventh week in Employee 2. The gonadotrophin titers in Employee 1 returned to normal levels by the thirty-fifth week, and titers were normal in Employee 2 at the 68th week. These changes reflect a temporary impairment of gonadal function which developed after exposure, with a return toward normal later in the follow-up. Aside from an isolated elevated LH titer for Employee 1 at the fourteenth week, LH excretion titers were normal for both Employees 1 and 2. Both the gonadotrophin and LH titers remained normal for Employee 3. Urinary estrogen excretion titers in each case were normal and remained so, with the exception of 1 observation in Employee 1 at the twenty-seventh week when no urinary estrogens were detected.

These studies thus indicate that Employee 1 sustained transitory gonadal damage which resulted in impaired spermatogenesis, histologic damage, and increased gonadotrophin excretion. Employee 2 sustained lesser damage which also returned to normal limits within 15 months after exposure, and Employee 3 had no significant abnormality in gonadal function.

Eye Effects[5]

Repeated slit-lamp visualizations revealed no opacities in any of the layers of the lens fibers. The exposure of Employee 1, who received the highest dose (384–468 rems) was below the threshold value for damage by X-rays set by the National Academy of Sciences (600–1000 r).

Blood Counts and Blood Chemistry[5]

The following hematologic procedures were employed: microhematocrit, hemoglobin, manual erythrocyte, manual leukocyte, differential, and platelet (phase) counts. Absolute neutrophil and lymphocyte counts were calculated. Blood counts were taken daily through Day 4 after the event, then 3 times a week through Day 27, twice a week through Day 55, weekly through Day 97, every other week through Day 181, and every fourth week subsequently through Day 365 and at 3-month intervals during the second year.

The only significant change in the level of a blood count was a depression in the absolute lymphocyte count of Employee 1. Values obtained in annual examinations for 5 years prior to the event and subsequent to 5 months after the event were predominantly in the range of 3000–4000. For the first several weeks after the event, his absolute lymphocyte values were predominantly between 1500 and 3000. The return to his normal range was gradual (Fig. 3). A temporary reduction in hemoglobin, PCV, and erythrocyte count values occurred in the case of Employee 3 immediately after an episode of hemorrhage at the testicular biopsy site. Irregular elevations in the neutrophil and platelet counts in the first few days after the event were considered nonspecific. Some 27 different blood chemistry examinations failed to reveal any significant abnormality in any of the 3 cases.

Studies on morphologically aberrant blood cells, using Wright-stained films of peripheral blood and bone marrow and Wright- and peroxidase-stained films of leukocyte concentrates, have been reported elsewhere[5] in detail and are summarized as follows.

The incidence of certain rarely occurring blood cells and more common types of cells showing relatively subtle morphologic aberrations was studied in peripheral blood specimens. When cells occur with extreme rarity, it is necessary to examine many thousands of their normal counterparts in order to be certain that the rate of occurrence has indeed increased. The types of aberrations observed included (1) changes in the nuclear structure of cells of the granulocytic series in peripheral blood and bone marrow; (2) increased immaturity of the monocytic series, as well as mild, transient monocytosis; (3) binucleate lymphocytes and lymphocytes with nuclear fragments; (4) increased numbers of plasmacytoid early mononuclear cells; (5) the occurrence of nucleated red cells in peripheral blood; and (6) chromatin and chromosome abnormalities in the marrow nucleated red cells. The magnitude of the changes observed when compared with changes observed in the Y12 and Lockport casualties described previously was seen to correspond most closely to the low-dose Lockport casualties.[5, 16]

1005477

Most of the changes represented direct radiation damage to either mature or stem cells. Aberrant forms were most numerous during the first 2 weeks after exposure. The occurrence of an occasional nucleated red cell in the peripheral blood is not readily explained, but may represent some alteration in the mechanism that normally excludes these cells from peripheral blood.

Bone Marrow[5] Smears of bone marrow and histologic sections of marrow particles were made 1, 7, 16, and 30 days after the exposures and were studied by routine hematologic methods. In general, neither sections nor the smears showed any profound damage. Employee 1 showed definite but not severe radiation effects. The bone marrow of Employee 2 appeared to show mild radiation effects and that of Employee 3 was considered normal.

Amino Acid Excretion

The study of amino acid excretion has been reported elsewhere[4] and is summarized here.

Proportional aliquots of 24-hr. volume urine specimens were taken and diluted to a common value. This allowed for a comparative analysis of the daily patterns. Quantitative analysis was accomplished by using a 2-phase descending solvent system. Chromatograms were stained, providing a polychromatic differential between the amino acids. The urinary amino acid patterns were visually compared to the patterns of large groups of normal individuals and also to a graded concentration of amino acid standards. The excretion patterns were studied with particular interest in the following amino acids: cystine, histidine, proline, tryptophan, glycine, serine, and β aminoisobutyric acid. These amino acids have been noted in abnormal concentrations in studies of other human radiation injuries.[27] No significant change in the excretion levels was observed in the present cases.

Chromosome Aberrations in Leukocytes

Analyses were made of chromosome aberrations induced in the peripheral leukocytes, because knowledge of the radiosensitivity of human somatic chromosomes has derived entirely from measurements made in vitro with various cell-culture systems. These cases provided a first opportunity to check the in-vitro observations against material irradiated in vivo. The

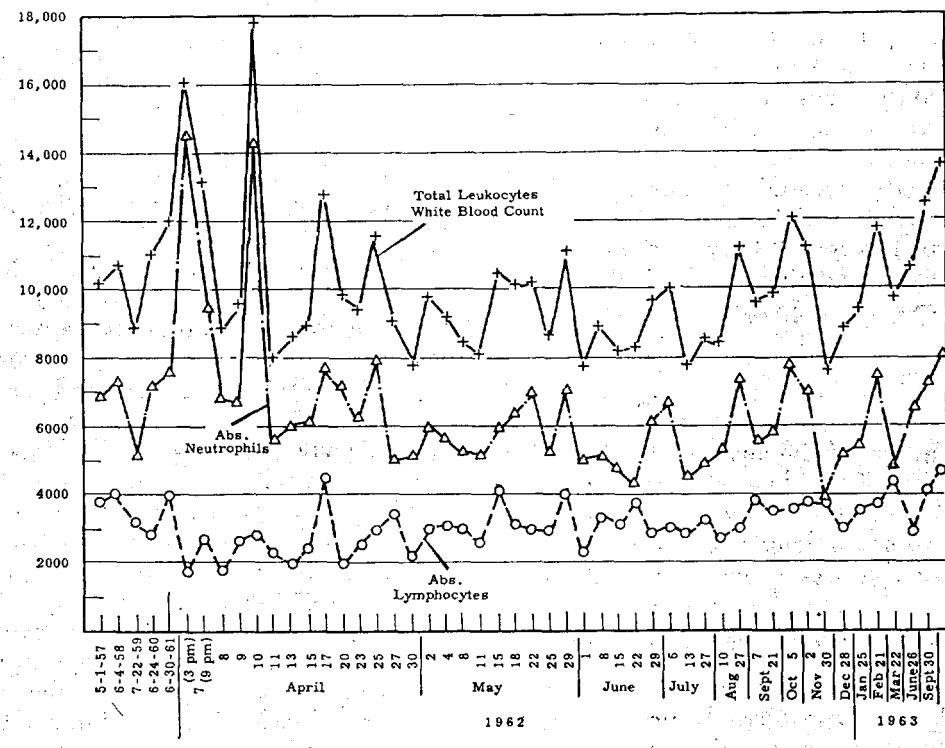

Fig. 3. Total leukocyte, absolute neutrophil, and absolute lymphocyte counts on Employee 1. Absolute lymphocyte values dropped during first weeks after accident from normal range of 3000–4000 to 1500–3000.

1005478

findings are reported in detail elsewhere[2, 3, 5] and summarized here. The future usefulness of analysis of somatic chromosome aberrations as a "biologic dosimeter" depends on having calibration checks in the form of actual measurements on irradiated subjects whose physical dose is reasonably well known, and also, to a lesser extent, on understanding the kinetics of loss and replacement of the cells used for analysis.

The standard leukocyte method was used for the preparation of mitotic figures suitable for analysis. Blood samples were collected at intervals from 4 hr. to 18 months after the accident. Spontaneous chromosome type aberrations have been found to occur rarely, if at all, either in culture or in circulation although spontaneous chromatid type aberrations are relatively frequent. It was thus possible to be sure that virtually all of the chromosome type aberrations in the leukocytes of irradiated subjects were induced in vivo by the radiation. Scoring of the aberrations was by visual inspection under low magnification for counting the chromosomes, noting breaks, dicentrics, and others (pericentric inversions, symmetrical translocations, etc.). The frequencies of chromosome type aberrations were much higher than normal control values. Both 1- and 2-hit types occurred. The dose estimates based on dicentrics correlated better with the physical dose estimates than the estimates based on deletions.

Comment

The infrequent occurrence of criticality accidents[28] makes it imperative for the physicians responsible for the care of exposed individuals to consider the scientific as well as the clinical implications of the event. It is obvious that the welfare of the exposed individuals is the physician's prime concern. However, in addition to caring for the patients, the physician should encourage scientific investigators to make appropriate studies in depth in their particular fields of interest. Early communication with the Divisions of Biology and Medicine and of Operational Safety of the Atomic Energy Commission facilitated contact with several of the investigators cited in this report, who were then able to initiate their studies soon after the accident.

The fact that the employees were actually wearing personnel dosimeters at the time of the accident makes this accident somewhat unusual. It also points up the difficulties inherent in arriving at the radiation doses for a criticality accident. In spite of the primary data available from the personnel dosimeters, the fixed dosimeters in the building, and the secondary information from sources such as neutron activation products and the whole-body counter, it was necessary to express the radiation doses in rather broad ranges. If less data were available, one would expect even greater uncertainty in the dose estimate. The value of the dose estimates would be greatly enhanced by improved knowledge of the effectiveness factors to apply to the absorbed radiation dose of both neutrons and gamma photons to determine the biologically effective dose for the effect under consideration. The physician should not demand more precision from the health physicist than his measurements allow. He should also be prepared to supplement the dose estimates with his clinical and laboratory observations, which take into account the factor of individual sensitivity to radiation.

Although attention is usually focused on the various blood counts and morphologic changes in the hematopoietic cells after an irradiation exposure, the effects on the gonads proved to be of greater interest in these cases. The absolute lymphocyte count experienced a modest decline. The bone marrow effects were nonspecific in the case of highest exposure. However, the same individual showed a pronounced fall in his sperm count, elevated gonadotrophin titers, and distinct damage in the seminiferous tubules of the testes. The individual who received the next highest dose showed no significant change in his blood counts but exhibited a change in hormonal levels and histologic damage. His sperm count was not followed, because he had previously had a vasectomy. In these cases the gonads showed greater evidence of radiosensitivity than the hematopoietic system. The importance of hematopoietic damage to the welfare of the patient remains unchallenged, but the investigation of the status of the testes after accidental radiation exposure deserves greater emphasis.

The blood counts in these cases demonstrated the value of establishing a base line by means of periodic employee examinations. The absolute lymphocyte count in Employee 1 dropped from its preliminary range to a lower level. Neither Employee 2, with a normal low level, nor Employee 3, with a normal higher level, showed any significant change in the lymphocyte count. Without base-line values all 3 employees would have been considered normal; the positive findings in Employee 1 would have been over-

1005479

looked. The previous study of the patient enables one to use the narrower normal range of the individual rather than the broad range of the population, thereby increasing the sensitivity of this indicator of damage. In the case of sperm counts, the pattern of damage evolves more slowly so that the base line may be established in the early period after exposure.

Summary

The results of extensive clinical and laboratory studies conducted over a period of 2 years on 3 employees exposed to radiation in a criticality accident are presented. The estimated whole-body doses ranged from 19 to 123 rems of mixed gamma and neutron radiation. Evidence of temporary radiation effects was obtained only in the gonads and hematopoietic system. The gonadal effects consisted of impaired spermatogenesis and increased gonadotrophin excretion. Hematologic effects included transitory bone marrow damage, a mild decline in the lymphocyte count in 1 case, and the production of morphologically aberrant blood cells. A significant increase in chromosome aberrations in the circulating leukocytes occurred. No ocular damage or increase in the urinary excretion of amino acids was observed.

Hanford Atomic Products Operation
Richland, Wash. 99352

References

1. Gamertsfelder, C. C., Larson, H. V., Nielson, J. M., Roesch, W. C., and Watson, E. C. Dosimetry investigation of the recuplex criticality accident. *Health Phys. 9:*757, 1963.
2. Bender, M. A. Chromosome aberrations in irradiated human subjects. *Ann. New York Acad. Sc. 141:*249, 1964.
3. Gooch, P. C., Bender, M. A., and Randolph, M. L. Chromosome Aberrations Induced in Human Somatic Cells by Neutrons. In: *Biological Effects of Neutron and Proton Irradiation,* Symposium, Vol. I, pp. 325-342. International Atomic Energy Agency, Vienna, 1964.
4. Ganis, F. M., and Howland, J. W. Observations on amino acid excretion in accidentally-irradiated humans. *Int. J. Radiat. Biol. 7:*107, 1963.
5. Fuqua, P. A., *et al.* Accidental Nuclear Excursion; Final Medical Report, HW-81010, 1964.
6. Hurst, G. S., Ritchie, R. H., and Emerson, L. C. Accidental radiation excursion at Oak Ridge Y-12 Plant. III. *Health Phys. 2:*121, 1959.
7. Hurst, G. S., Ritchie, R. H., Sanders, F. W., Reinhart, P. A., Auxier, J. A., Wagner, E. B., Callihan, A. D., and Morgan, K. Z. Dosimetric investigation of the Yugoslav radiation accident. *Health Phys. 5:*179, 1961.
8. Harris, P. S. Acute radiation death resulting from an accidental nuclear excursion. VI. Dosimetric calculations. *J. Occup. Med. 61:*178, 1961.
9. Auxier, J. A. *Dosimetric Considerations in Criticality Exposures. Proceedings of a Scientific Meeting Jointly Sponsored by the International Atomic Energy Agency and the World Health Organization, Geneva, Oct. 1960,* pp. 141-150. Columbia, 1961.
10. Cronkite, E. P. Radiation trauma. *Maryland Med. J. 12:*393, 1963.
11. Norwood, W. D. Radiation accident, injury or fear. *Northwest Med. 63:*243, 1964.
12. Bond, V. P., Fliedner, T. M., Cronkite, E. P. Evaluation and management of the heavily irradiated individual. *J. Nucl. Med. 1:*221, 1960.
13. Thoma, G. E., Jr., and Wald, N. The diagnosis and management of accidental radiation injury. *J. Occup. Med. 1:*421, 1959.
14. Andrews, G. A., Sittersen, B. W., Kretchmar, A. L., and Brucer, M. Accidental radiation excursion at the Oak Ridge Y-12 Plant. IV. Preliminary report on clinical and laboratory effects in the irradiated employees. *Health Phys. 2:*134, 1959.
15. King, E. R. The clinical evaluation and management of radiation accident exposure patients. *Radiology 77:*77, 1961.
16. Ingram, M., Howland, J. W., Hansen, C. L., Jr., Mermagen, H., and Angel, C. R. Influence of continuing clinical observations on dose estimates one year after radiation accident. *Health Phys. 8:*519, 1962.
17. Andrews, G. A. Criticality accidents in Vinca, Yugoslavia and Oak Ridge, Tennessee. *J.A.M.A. 179:*191, 1962.
18. Lushbaugh, C. C. Acute radiation death resulting from an accidental nuclear critical excursion, gross and microscopic pathology and neuropathology. *J. Occup. Med. 3:*150, 1961.
19. Wilson, R. H. A Method for Immediate Detection of High Level Neutron Exposure by Measurement of Sodium-24 in Humans, HW-73891, June 1962.
20. Wilson, R. H., Milligan, V. M., Unruh, C. M., and Larson, H. V. Gamma Calibration and Evaluation Techniques for Hanford Beta-Gamma Film Badge Dosimeters, HW-71702, Sept. 1960.
21. Recommendations of the International Commission on Radiological Protection, as amended 1959 and revised 1962. ICRP Publication 6, Pergamon, London, 1964.
22. Neary, G. J. The Significance of the Rem and Parameters on Which it Depends. Symposium of the Joint Health Physics Committee on Protection Measurements: Appropriate Units and the Interpretation of Instrument Readings. Medical Research Council, Radiobiological Research Unit, Harwell, Berkshire, England, Nov. 1962.
23. Bond, V. P., Carter, R. E., Robertson, J. S., Seymour, P. H., and Hechter, H. The effects of total-body fast neutron irradiation in dogs. *Radiat. Res. 4:*139, 1956.
24. Alpen, E. L., Shill, O., and Tochilin, E. Hematology and LD_{50} of dogs exposed to neutrons from the $_4BE^9(p,n)_5B^9$. *Radiat. Res. 9:*85, 1958.
25. Alpen, E. L., and Baum, S. J. Autologous bone-marrow implantation after fast neutron irradiation of dogs. *Radiat. Res. 11:*383, 1959.

1005480

26. MacLeod, J., Hotchkiss, R. S., and Sitterson, B. W. Male fertility after sterilization by nuclear radiation. *J.A.M.A. 187*:637, 1964.
27. Rubini, J. R., Cronkite, E. P., Bond, V. P., and Fliedner, T. M. Urinary excretion of beta aminoisobutyric acid (BAIBA) in irradiated human beings. *Proc. Soc. Exp. Biol. Med. 100*:130, 1959.
28. Saenger, E. L. Medical Aspects of Radiation Accidents. U. S. Atomic Energy Commission, U. S. Government Printing Office, Feb. 1963.

Bibliography

Ingram, M., Adams, M., Coonan, L., Jespersen, J., Nielsen, G., Pratt, D., and Yettewich, G. The occurrence of lymphocytes with bilobed nuclei in cyclotron personnel. *Science 116*:706, 1952.

Ingram, M. The occurrence and significance of binucleate lymphocytes in peripheral blood after small radiation exposures: Proceedings of the Symposium on Immediate and Low Level Effects of Ionizing Radiations, Venice, Italy. *Int. J. Radiat. Biol.* Special Suppl., 1960.

Ingram, M., and Howland, J. W. Some morphological peculiarities of blood cells in man following accidental X-irradiation. (Abstr.) *Radiat. Res. 16*: 585, 1962.

Ingram, M., and Preston, K., Jr. Importance of automatic pattern recognition techniques in the early detection of altered blood cell production. *Ann. New York Acad. Sc. 113*:1066, 1964.

Fliedner, T. M., Andrews, G. A., Cronkite, E. P., and Bond, V. P. Early and late cytologic effects of whole body irradiation on human marrow. *Blood 23*:471, 1964.

1005481