EXPERIENCE WITH RADIATION ACCIDENTS IN OPERATIONS DIRECTED BY THE UNITED STATES ATOMIC ENERGY COMMISSION

W. T. Doran, Jr., M.D., Division of Operational Safety
and
H. D. Bruner, M.D., Division of Biology and Medicine

A radiation accident may involve persons only, or it may involve equipment or the environment alone, or any combination of persons, equipment and environment. For the purposes of this paper, we shall confine our observations, for the most part, to those events that have involved persons to the extent that they required medical attention.

Nevertheless, we emphasize the great importance of the physician always being kept informed of details of those accidents which involve only equipment or environment, because frequently it is only by chance that such accidents did not also involve persons. Although the amount of irradiation or isotope release may have been small in a particular accident, it is important to know why it occurred since a little more radiation released in similar circumstances could be very serious indeed. When physicians seek to learn from accidents involving only equipment or environment, they should analyze the details in the light of how persons might have been affected, had they been present; what preventive measures should be taken in the future; and what medical action should be preplanned to assist any possible victim. For example, instances of stack-releases of tritium or a bench-spill of plutonium, even though persons were not involved, should be reviewed in the light of whether protective clothing and respirators should be worn by employees during such operations in the future. Or, assuming that a worker had inhaled tritium, what amounts of fluids should be forced; should diuretics or chelating agents be used; how frequently should bioassays be performed; is hospitalization needed, etc., etc.

For this discussion, we shall divide radiation accidents into two basic types. One type is that in which a person is irradiated without any radioactive material coming into contact with the body. In the other type, radioactive materials do come into contact with the body or enter it. Further, we shall eliminate incidents in which radium, or uranium and thorium ores have been involved. As reasonable cut-offs for the lower level of radiation which may have medical significance, we have taken 15 or more rem whole body for external irradiation; for irradiation from internally-deposited body burdens of radioisotopes we have taken one-half of a body burden, as defined by the ICRP.

To show the extent and characteristics of the USAEC experience[1,2] in radiation accidents we will present three tables. The first is an adaptation and updating of a table originally compiled by Gerstner[3] in 1957. This table shows the number of events and number of persons with respect to the calculated or measured radiation doses, the medical experience that resulted, and the clinical course in terms of prognosis. The table could be amplified by the histories of persons exposed to a fallout field, of persons receiving documented whole body therapeutic irradiation (at least 750)[4] and of a few volunteers. The data from all these clearly confirm the medical observations made on persons involved in the listed accidents.

Three points shown in Table I should be emphasized. The first is that persons receiving whole body irradiation amounting to 150 rem (or possibly 200 rem) or more should always be hospitalized; where the dose is less than 150 rem the people can probably be handled successfully on an outpatient basis unless clinical research procedures are to be carried out. Doses of less than 25 rem are not likely to show even transient significant effects, even sensitive reactions such as chromosomal changes. Since the clinical picture of acute radiation sickness reported from multiple sources agrees with the data from experimental animals, we believe that the patterns of reaction by the various tissues are reasonably true and can be used as a basis for therapy and somewhat more cautiously for prognosis. However, our present knowledge of delayed effects based on experiences with man exposed to very low dosage levels, does not warrant prognosis about fertility, genetic damage, cataracts, longevity or other possible long-term chronic reactions.

There is a mild,early, reaction by the radiosensitive hematopoietic system expressed as a transient lymphopenia in individuals who receive a whole body exposure of about 50 rem. With larger doses the reaction is more prompt, extensive and involves all other cell types. Therefore, such persons should receive immediate, repeated complete hematological studies, even though there are no clinical symptoms or signs of irradiation. The blood studies should be documented, examined by consultants, and entered in the individual's personal health record for medicolegal reasons. Extensive researches are being carried out to determine whether whole body irradiation can be distinguished from local or fractional irradiation and whether the size of the exposure can be estimated by biochemical tests, especially those based on the excretion of unusual kinds or amounts of amino-acids in the urine (hydroxyproline, cystine, taurine, beta-amino isobutyric acid, etc.). As of now nothing definitive has been demonstrated to be related to level of exposure, but all urines should be collected and frozen for study by the physician or his colleagues.

When there has been a single exposure of no more than 25 rem we are inclined to allow the man to continue working with radiation especially if the permissible cumulative exposure of 5(N-18) rem (where N represents the worker's age) has not been exceeded.

If the dose is 200 rem or more hospitalization is certainly indicated, and some degree of the acute radiation syndrome as described by Thoma and Wald[5], Shipman[6], Hempelmann[7], Hasterlik[8], and Brucer[9] will be observed. Naturally, the larger the dosage the more abrupt, intense, and protracted is the syndrome. When the radiation dosage lies between 400 and 800 rem whole body, and especially between 600 and 800 rem, death is expected to occur no matter what therapy is instituted. But since there have been few exposures in this latter span it is exactly the one in which we have least experience. If the spleen, liver, or parts of the bone marrow are protected and escape being irradiated, the chances of survival with "large" doses increase greatly. The lessons to be emphasized are the importance of keeping the victims in individual private rooms and using sterile procedures; allowing restricted visits from next of kin only; and instituting immediate and continuing clinical and laboratory observations. Particular attention should be paid to collecting a 50 milliliter sample of blood for Sodium 24 assay, if neutrons have been involved; the urine should be saved for biochemical analysis. Changes in the peripheral blood, their appearance, severity and rapidity of change and the nature and timing of clinical signs such as nausea, vomiting and fatigue should be recorded since they are the basis for determining the general range of exposure, individual reaction to exposure, and probably prognosis.

Superior nursing and sedation, as needed, do much to control the inevitable psychic reactions of the patient and stabilize him. Often the patient's family requires medical assistance. The number of casual visitors and interlopers may be quite surprising.

Finally, it is well to have established working relations with the local newspapers and/or public relations people, so that journalistic sensationalism will be kept to a minimum.

When early health physics and medical observations suggest very high whole body dosages with still a chance of survival, early treatment in the form of as nearly isologous as possible bone marrow transplants should be instituted immediately even though the result of such therapy may be hazardous if the irradiation dose is not high enough to inhibit the immune mechanisms.

If there is a discrepancy between the radiation dose as computed from instruments by the health physicist and the dose judged from the clinical reactions of the patient, we believe that the clinical judgment should prevail. Radiation sensitivity varies from patient to patient and besides the treatment is based on symptomatic principles.

Even though death appears to be an inevitable outcome, the physician responsible for therapy is justified in any and all therapeutic procedures. Only from such studies may medicine look forward to progress in saving lives endangered by apparently lethal doses of radiation. The American attitude has been to use therapy only when it was clearly indicated; the European approach seems to be the employment of many procedures and drugs. But since good results have followed both regimes it does not seem worthwhile to argue over which is better--especially since symptomatic-replacement concepts are our only guides to therapy.

The second point to come from this table is the lack of knowledge about the signs or symptoms in persons whose radiation dosage was 1000 rem and over, and hence this is left blank. Three of these cases were SL-1 victims who died very quickly from the mechanical effect of a criticality. They would, unquestionably, have died of radiation, if the traumatic effect had not predominated; there were no observed radiation effects in these people. The fourth person was involved in the 1958 criticality at Los Alamos. The dose to the head was estimated to be in the region of 12,000 rem and he exhibited an immediate cerebral (CNS) depressant state with death ensuing in 35 hours as described below. Acute depression of the CNS undoubtedly predominates following doses above 3000 rem but we are lacking clinical information about reactions to doses in the range of 1000 to 3000 rem. Extrapolation from animal experiments point to the so-called "gut death"; inferences from the experiences at Hiroshima and Nagasaki are more confusing than helpful.

The third point illustrated by the table is the paucity of exposures having medical significance, considering the 19 year existence of the industry. In the nuclear energy industry in the USA since 1943, there have been 230 fatal accidents of which radiation *per se* was responsible for only 3* and each of these deaths was the result of a criticality incident. In over 3 billion man-hours of work at risk, there have been only 10 incidents in which 41 persons received more than 15 rem exposure acutely, and only 14 persons received exposures of over 200 rem.

Each fatal incident provided valuable lessons. The first Los Alamos accident occurred during a criticality experiment in 1945. Two persons were exposed to a mixture of fast neutrons and gamma-rays calculated to give doses of 590 and 31 rem, respectively. The man who received 590 rem and died 24 days later dropped a tool on the assembly and started the chain reaction; he might have survived had he not at once reached in reflexively to disassemble the experiment and stop the reaction. As a result of this experience all such procedures are now carried out by remote control in such a way that the assembly may be automatically dumped; no longer can a worker manually dismantle an experiment of this nature. Because no film badges were worn, the dose had to be computed from the amount of Sodium 24 activated from Sodium 23 in the blood. Then, as now, a number of assumptions go into the calculations and confidence in its precision is not high. Nevertheless it is better than nothing and should be attempted; hopefully activation foils would be strategically placed wherever criticalities might occur, so that the health physicist will have data on neutron flux and spectrum for calculations.

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* As noted before we do not consider the SL-1 deaths due to radiation.

The second Los Alamos accident, 9 months later in 1946, was an accidental criticality, also. A scientist manually brought the critical parts together, while demonstrating to a student their physical relationships. Since then there has been strict enforcement of the rule that a dangerous maneuver can never be used as a teaching device.

The third fatality took place in Los Alamos in 1958. During the course of a routine Plutonium 239 salvage operation, the slurry was stirred into a critical configuration and delivered a mixture of neutrons and gamma radiation to the operator as he stood over the cylindrical reaction vessel. Since he was alone at the time it was not at first realized that he was exhibiting an immediate cerebral reaction to the large pulse of radiation estimated to be 12,000 rem to the head. Because of his confusion and his statement that he was "burning up inside", his rescuers first thought of chemical intoxication rather than radiation. The accident, which was no fault of the operator, resulted in redesign of equipment so that sludge cannot collect and be stirred up into a small homogeneous reactor.

In the SL-1 accident it appears that a control rod was withdrawn during a manual refueling operation of a small water-moderated reactor. The resulting generation of steam blew some of the elements out of the cauldron and the combination of blast and missiles killed two men outright and the third died shortly afterward. Even if they had not died of trauma, it is likely that they would have died of radiation since the reactor and its shell were highly contaminated by fission products. Further, radioactive particles were strongly embedded on and in the bodies of the three men--so much so, in fact, that those who would have rescued and treated them would have been exposed to such high doses of radiation from the clothing, hair, and bodies of the men, that little could have been done except by remote control.

This accident is archtypical of the uncertainty of radiation accident problems. It demonstrates how really unprepared we all are for unexpected complications that can result from a radiation accident. Nothing in all our previous experience had prepared us to be able to act effectively in the presence of such a very highly contaminated environment or to treat highly contaminated people.

We must recognize that we were not, and still are not, prepared to cope with contamination of that magnitude. For example, how can we remove large amounts of contamination that have been driven into the skin along with grease? Should one amputate limbs to reduce the general whole-body dose? How can contaminated hair and clothing be removed quickly by remote control? Is it more important to try to remove heavy surface contamination before repairing severe lacerations or vice versa--assuming that one can approach closely enough to do either? We do not have the answers to these and many other obviously fundamental questions.

A partial list of USAEC experiences with other contaminating incidents is given in Table II. The list is partial because incidents often escaped detection in the early days before it was fully realized what kinds of hazards existed. As a matter of fact, formulation of the concept of the "Internal Emitter Hazard" by the ICRP is a relatively recent thing and basic ideas about it are still being evolved.

The most unfortunate aspect of this subject, of course, is our inability to state precisely what is the body burden of most of those radioisotopes which are the most frequent contaminants. The whole body counter is a very valuable tool if the radioisotope has a reasonably short half-life and a detectable gamma-ray spectrum. (We believe any major nuclear production installation should have access to one.) Otherwise, we must depend on urine or fecal assays to provide an estimate of the body burden. A great deal of research on excretory rates still has not given us factors which can be translated into reasonably precise body burdens. Nevertheless, they are employed as best they may and they have come to have some medicolegal status.

It should always be recognized that body burden data are subject to considerable uncertainty and should always be so qualified.

The state of our knowledge is best illustrated by the fact that most of the biological half-lives listed in the ICRP tables are based on estimates of many kinds rather than on measurements made on man.

It will be noted from Table II that a certain few radioisotopes are involved. This is because the permissible body burden is so very low to begin with (Plutonium, 0.04 μc), the material is intrinsically difficult to control (Plutonium, Iodine, Ruthenium), or such large qunatities are handled. In connection with control, we have observed that the number of instances of contamination decreased abruptly when negatively pressurized glove boxes were substituted for the original simple-enclosure design. The 27 instances of partial body burden from Los Alamos are men who used the older design glove boxes. Some were never involved in an accident or spill or breakdown of routine control; still, only a few tiny, aerosolized particles could account for their body burdens.

A number of lessons become evident on studying the records condensed into Table II. First, it is difficult, or impossible, to decide what denominators to use for making comparisons of incidence: Should incidence be based on total plant man-years; scientific man-years; man-years of those working with radioisotopes; number of times per day or year that operations involving radioisotopes offer a potential hazard, or what? In the absence of such points of reference the data in Table II should be regarded only as illustrations of what can happen and the order of magnitude.

Second, considering the opportunities, it is remarkable how few body burdens have exceeded the ICRP maximal permissible burdens. We submit, however, that the numbers could enlarge rapidly if our industrial hygiene measures were relaxed.

Third, the most frequent cause of contaminating accidents seems to be a fault on the part of the worker, followed by accidental explosions, breakage of glass containers and no known reason. Generally, the person is aware of having become contaminated, but sometimes the contamination is detected on routine bioassay.

Fourth, the respiratory system seems to be the most significant route of ingress of contamination, although it is the one we know least about. Evidence at hand shows that some inhaled aerosols can be absorbed into the blood stream, while other particles are coughed up and expelled, or swallowed; still others will be taken into the tracheo-bronchial lymphatics much like carbon infiltrates the lung. Since tiny, weak deposits of radioisotopes in the lungs of experimental animals can produce adenomas and bronchogenic cancers, pulmonary contamination is a matter of real concern.

Fifth, the physician can often reduce the body burdens by appropriate therapy. Certainly he can effectively hasten the excretion of Tritium and Iodine and to a much less degree the removal of Strontium, Plutonium, and other bone seekers. The moderate success achieved by intravenous chelating agents encourages further research. Poorly soluble radioisotopes injected beneath the dermis or into lacerations should be promptly excised, if at all possible; debridement guided by radiation detectors can be very effective if done at once.

Thus far, no clinically detectible changes have been linked with the internal contaminations in these people, but it is too soon to make statements or claims about harm or lack of harm.

Generally, the spills and environmental contaminations that accompany contamination of personnel are minor and easily cleaned up. There have been other contaminations, however, which produced widespread, costly contamination while only slightly contaminating workers. The SL-1 accident would have been the prototype in which both workers and environment were heavily contaminated.

Finally, it is conceivable that failure of control of effluents in a plant handling radioisotopes or fission products would result in deposits of radioactivity off the plant site which then might get into the food chains of the civilians. This is most likely to happen where the plant sits in the middle of a densely populated locale. The only solution to this is to establish routine sampling networks which will alert the proper public authorities to take whatever actions are deemed necessary.

Table III gives an indication of the relative frequency of all kinds of accidents in operations directed by USAEC, comparing the number of those involving persons to the total number of accidents, July 1958 through June 1962. These are subdivided into two groups: those occurring in government-owned and operated plants and facilities, and those occurring in USAEC licensee operated, that is, privately-owned facilities.

In some instances one individual has been affected in an accident; in others several. In all, 184 individuals were affected in 83 out of a total 127 incidents in the 4 years. The largest single group was the 8 persons involved in the SL-1 rescue and service operations.

The problem of single exposure incidents is much larger than that of cumulative exposure as seen in this table. However, we feel it safe to predict an ever increasing number of isotope users will tend to show more cumulative exposure excesses unless they recognize and accept the necessity of a carefully managed, continuing program of film badge and bioassay monitoring of the individual, and a consistent--or where possible, an automatic--monitoring of the environment.

At the extreme right in Table III are numbers of persons receiving radiation in so-called "Type A" and "Type B" events. These categories are useful administrative conventions whose primary purpose is to ensure speedy reporting of significant events to USAEC Headquarters[10]. Factors are dosage received, number of persons affected, property value loss, and public relations significance. Suffice it to say that these reporting requirements are a factor in the constant vigilance of all concerned, which underlies the excellent record of the industry in the United States. That record, mentioned earlier in this paper, of only 3 fatalities due to radiation *per se* in the 19 years of the industry's existence, is no accident. From the very beginning the policy was to "maintain strict control over the manner and methods of work...which should result in the prevention of all conditions associated with delayed injurious effect".

The outstanding characteristic in our experience was the unpredictability of the operation errors which in all cases were the source of difficulty. In every case the accident has been the result of an error, completely unpredicted, but in retrospect a situation that can be protected against in the future.

Under the limitations of our present knowledge, we can only stress the importance of preplanned operations for all phases of the industry, including preventive medical and rescue and medical care operations.

Safety measures include use of hoods, adequate exhaust, enclosed processes with negative air pressures, work within cells by remote control, protective clothing, use of hand and foot counters and continuous environmental monitoring, with identification and marking of high radiation areas as well as strictly controlled access to them.

On the medical side, the responsible physician must have preplanned and rehearsed procedures that include methods to determine quickly the types and amounts of radiation released. Coordination of preplanning with the health physicist is essential. Two calibrated instruments to measure radiation of all types should be readily available to the site of an accident. The extent of potential hazard to rescuers and therapists must be determined or estimated. Protective clothing, respirators, etc. for rescuers should be stockpiled for immediate accessibility. Advance planning makes provision for containment of victims for emergency and continued therapy without exposing rescue and therapy personnel to radiation exceeding 150 rem/hour for one hour only.

Complete hematological studies on all persons with over 50 rem exposure should be made and documented in the individual's health record. Those exposed to 150 to 200 rem or more should always be hospitalized. If possible, whole body counter measurements should be made. All body excretions should be collected, measured and assayed for radiological, chemical or hematological values and trends of change. Sodium 24 assay of blood should be done if neutrons were involved. Appearance, severity, and rapidity of changes in peripheral blood, and nature and timing of clinical signs should be recorded as a basis for determining general range of and reaction to exposure and prognosis.

In cases of very high whole body dosage with still a chance of survival, immediate treatment with bone marrow transplants should be instituted even though hazardous from the standpoint of immune reaction. Beyond this, we must rely upon the clinical judgment of the responsible physician using the symptomatic-replacement concepts which are our only guides to therapy.

Much research remains to be done to give us the knowledge and the tools necessary to determine precise body burdens of many radiation contaminants; how to decontaminate quickly a high dosage radiation accident victim; to devise effective means to prevent contamination--particularly respiratory system contamination; and to give us answers to the many related problems.

W. T. Doran, Jr., M.D.
H. D. Bruner, M.D.
Washington, D. C.

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TABLE I

Radiation Dosage and Clinical Response to
Exposure to Radioactive Materials Outside the Body

Dose Range (rems)	Persons	Incidents*	Signs & Symptoms	Clinical Course
15 - 49	16	1, 2, 3, 4, 5, 7, 8, 10	No prodromal phase Slight lymphopenia	Insignificant
50 - 99	6	2, 3, 4, 6, 9	Prodromal phase in some slight leucopenia	Insignificant
100 - 149	3	2, 3, 6	Mild leucopenia	Mild, ambulatory
150 - 199	2	2, 3	Some prodromal; definite leucopenia	Mild, ambulatory
Hospitalization threshold				
200 - 399	2	4	Fully developed hemopoeitic form	Moderate to grave
400 - 599	5	1, 2, 4	Hemopoeitic and gastrointestinal forms	Severe; 1 fatality
600 and over	5	2, 6, 10		Lethal
Data inadequate	2	2, 9	**	
TOTAL	41	10		

* Incidents numbered in chronological order: 1) Los Alamos; 2) Los Alamos; 3) Argonne; 4) Oak Ridge; 5) Los Alamos; 6) Los Alamos; 7) Livermore; 8) Nevada; 9) Sandia; and 10) Idaho SL-1.

** Severe surface reaction, face and hands in one; no whole body estimate.

W. T. Doran, Jr., M.D.
H. D. Bruner, M.D.
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TABLE II

Partial Tabulation of Contaminative Incidents Greater Than 0.1 to 0.5

Maximal Permissible Body Burdens Initially in USAEC Directed Operations, 1943-1962

Isotope	No. Persons	Type Operation	Route	Notes
Sr^{90}	1	Research	Respiratory	Aerosol from drying solution on hotplate. Concentration in urine decreased by 500x in 4 wks. Barely detectable at 300 days.
T^3	1	Research	Oral	Intake of 153 mc. Treated by Hg diuretic, NH_4Cl and 8 l. H_2O/day. Biological half-life observed to be 8.5. Below detection in 117 days. Total body dose $\cong$ 10.3 rem.
Am^{241}	2	Research	Skin-1 Probably respiratory-1	One contaminated puncture wound excised. EDTA removed 90% of estimated 25x body burden. One origin unknown; well fixed in bone + elsewhere when discovered. Burden probably 4x MPBB.
Cm^{242}	4	Research	Respiratory	High level spill in defective glove box. Concentration in urine decreased 10x in 100 days. No treatment. Others probable inhalation of air from a glove box. Rapid-60 day-decrease of excretion in urine to "not detected".
I^{131}	11	Research & production	Respiratory	I^{131} detected by scanning. Burdens estimated at 1-39 μc. Estimated thyroid doses 5-240 rad. Stable I and methimazol useful in reducing thyroid uptake and shortening biological half-life.
Pu^{238}	3	Production	Respiratory	Body burdens less than 0.1x but continued low level excretion for 2 years.
Pu^{239}	64	Research & production	Respiratory-21 Skin-10 Skin & Respiratory-30 Uncertain-3	Only 5 greater than 1 body burden and 7 at 0.5 to 1 body burden. DPTA found more effective than EDTA. Second course of DPTA effective but not as great reaction. Initial body burdens of 7.7 and 2.7x reduced to less than 1 by local excision guided by spectrometer; body burden of 0.5x reduced near zero by excision. 26/27 cases followed 15 yrs. cont. low excret.

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TABLE III

Incidents Involving Radiation
AEC Operations and AEC Licensee Users
July 1, 1958 -- June 30, 1962

	TOTAL			SINGLE EXPOSURE CONTAMINATION						CUMULATIVE EXPOSURE CONTAMINATION						Persons Involved Type	
				Total		External		Internal		Total		External		Internal			
	Incidents	Incidents affecting persons	Persons	Inci-dents	Per-sons	Inci-dents	Per-sons	Inci-dents	Per-sons	Inci-dents	Per-sons	Inci-dents	Per-sons	Inci-dents	Per-sons	A	B
TOTAL	127	83	184	61	149	18	77	28	62	22	35	6	7	6	17	45	139
AEC Operations	41	22	78	19	75	9	45	10	30	3	3	2	2	1	1	22	56
Licensee Users	86	61*	106*	42*	74*	9	32	18	32	19*	32*	4	5	5	16	23	83

* Totals reported by Licensee Users include certain incidents of "point exposure" not listed as either external or internal contamination.

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