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RAPID ESTIMATION OF FAST NEUTRON DOSES FOLLOWING RADIATION EXPOSURE IN CRITICALITY ACCIDENTS. THE $^{32}S(n,p)^{32}P$ REACTION IN BODY HAIR*

By

Donald F. Petersen

Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico

1. Introduction

Despite availability of highly sophisticated physical dosimetry, accidents involving serious exposure to neutrons invariably have occurred in the absence of adequate dosimetry systems. In the earliest cases reported by Hempelmann and his associates [1], neutron dose estimates were based on blood sodium activation. Subsequent incidents have similarly relied on activation measurements conducted on biological material. These procedures have been reviewed by Hurst and his associates [2] and by Auxier [3]. In the fatal 1958 nuclear-critical accident at the Los Alamos Scientific Laboratory [4], blood sodium activation provided an early indication of the magnitude of the dose. It also provided the stimulus for investigation of an additional biological indicator: ^{32}P production by bombardment of hair sulfur with fast neutrons [5]. Data from subsequent incidents, together with studies on improved analytical methods, form the basis for this report.

In view of the high cystine and consequently high sulfur content of human hair, it was reasoned that after suitable chemical

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isolation ^{32}P beta activity arising from neutron capture by sulfur in the $^{32}S(n,p)^{32}P$ reaction could be determined and the exposure to neutrons with energies above the sulfur threshold computed. Estimates of the fission neutron spectrum could then be employed to provide an approximation of the total gamma-neutron exposure of sufficient accuracy for establishing a prognosis and course of treatment.

2. Method

Hair, nails, and cartilage (near the surface of the body) possess sufficient sulfur to be useful for incident fast neutron dose estimates. However, of these materials, hair is the only one readily available in sufficient quantity to permit prompt post-exposure analysis and has been used almost exclusively in these experiments. Appendix I is a summary of the steps essential for arriving at a preliminary dose estimate in the event of an accidental exposure to fast neutrons. The procedure is intentionally described in sufficient detail to be adequate for providing a neutron dose estimate without reference to other literature cited. The procedure has been simplified in an attempt to accelerate the method as much as possible with a view toward obtaining preliminary neutron dose estimates with approximately the same rapidity as blood ^{24}Na measurements.

Individual hair samples were obtained from local barbershops and from the obstetrical and surgical services of the Los Alamos Medical Center. For controlled experiments, anatomically authentic hair samples were placed in polyethylene envelopes and appropriately positioned on a plastic mannequin filled with tissue-equivalent solution. With the exception of two experiments conducted during the Kiwi reactor test series at the Nevada Test Site, all experimental samples were exposed to the fission spectrum of Godiva, an unshielded Los Alamos critical assembly. Sulfur was determined colorimetrically with barium chloranilate [6], and total phosphorus was determined by the method of Fiske and Subba-Row [7]. In two of four accidents for which sulfur activation data have been obtained, gross contamination with mixed fission products necessitated isolation of ^{32}P in radiochemically pure form. Decontamination consisted of alternately precipitating ^{32}P

in the presence of a known amount of carrier phosphate as zirconium phosphate and as ammonium phosphomolybdate essentially as described by Bonner and Potratz [8].

3. Results

Human hair may be employed for the detection of fast neutrons in essentially the same manner as a sulfur threshold detector and is subject to the same restrictions in interpretation. To be used successfully, the amount of sulfur present must be known, the amount of stable phosphorus present must be extremely low, and an estimate or independent knowledge of the neutron spectrum must be available. If the neutron spectrum is known, useful estimates of total dose can be obtained. However, even in the absence of an accurate description of the spectrum, it is possible to determine dose distribution from the relative specific activities of samples from various parts of the body. Such information, as will be shown later, may be useful in deducing the position of an individual with respect to a fast neutron source. With these requirements in mind, a large number of sulfur and phosphorus analyses were performed to establish whether the sulfur content of human hair was sufficiently uniform to obviate the necessity for individual sulfur measurements.

Results in Table I demonstrate that the sulfur content of human hair is remarkably constant, regardless of color or anatomical distribution. The phosphorus content was more variable in unwashed samples due to external contamination and epidermal debris. Washing the samples on a Buchner funnel with a detergent, followed by rinsing in distilled water and alcohol, reduced the phosphorus content to less than 1 per cent of the corresponding sulfur value. It was concluded therefore that, with the possible exception of extreme spectrum degradation, phosphorus activation could be disregarded as a significant source of beta activity.

Table II summarizes results of sulfur and phosphorus measurements on samples taken from various anatomical locations of a single individual. These data emphasize the constancy of composition and support the idea that neutron dose distribution can be

determined by separate analysis of small samples from various anatomical locations without resorting to separate sulfur determinations.

Data shown in Table III compare neutron doses estimated from hair ^{32}P activity with that obtained from ^{10}B-clad ^{239}Pu, ^{237}Np, ^{238}U, and sulfur threshold detectors, the Hurst proportional counter, tissue-equivalent and graphite-CO_2 ionization chambers, and a calibrated fission counter [9]. For this series of analyses, agreement with physical referee dosimetry was sufficient to provide useful dose information over a wide range of incident doses.

An additional facet of interest from a practical standpoint is demonstrated in Table IV, where hair samples were positioned at 90-degree intervals around the head, chest, and pelvic area of the mannequin and exposed to a prompt critical burst from the Godiva assembly. After exposure, the analyst was required to deduce the position of each sample, as well as to estimate the dose. The data demonstrate that accurate positioning, as well as acceptable dose estimates, were achieved.

4. Results from Criticality Accidents

Physical details of four critical excursions resulting in significant exposures of 11 people with five fatalities (Los Alamos, 1958; SL-1, 1961; Hanford, Recuplex, 1962; and Wood River Junction, United Nuclear Corporation scrap processing plant, 1964) have been reviewed by Stratton [10]. Clinical details of the Los Alamos accident were presented at the 1961 Geneva Symposium by Shipman [11]. A summary of the SL-1 accident has been published [12], though it is of little clinical interest since none of the personnel survived for an appreciable period. A preliminary report of physical conditions and dosimetry is also available for the Wood River Junction, United Nuclear Corporation (UNC) accident [13], but detailed reports have not yet been released.

Fast neutron dosimetry by hair analysis was performed by the author on samples taken at autopsy from victims of three of the above-mentioned accidents. In addition, two less severely irradiated

individuals involved in the UNC accident were also measured, and the fact that they had been exposed to fast neutrons was confirmed. All three accidents emphasize a point of significant clinical importance, namely, that in each case of fatal exposure dose distribution has been markedly asymmetric.

Dose estimates made on personnel involved in the SL-1 accident (Table V) were of little significance from a radiobiological standpoint, but the relative specific activities of hair samples obtained at autopsy from each of the victims were very helpful in deducing their position on the reactor top at the time of the critical excursion and subsequent explosion. When used in conjunction with a reconstruction based on observed superficial wounds, the data obtained in Table V enabled us to conclude that the position of each man was compatible with the duties in which he was presumably engaged. Assuming that the spectrum of the SL-1 accident might resemble that emanating from the Sandia port of the Los Alamos Omega West reactor, total fission yield was estimated to be 3×10^{18}. When the cobalt flux wires were finally retrieved during the dismantling of the reactor, a total fission yield of 3.1×10^{18} was found.

Data in Table VI show that the dose delivered to the head and thorax of the operator involved in the Los Alamos accident was significantly higher than the dose measured by activation of pubic hair. The Los Alamos and UNC accidents were similar in that both were excursions in homogeneous systems, both resulted from errors in the manipulation of fissile material in scrap reclamation processes, and both appear to have been of the same order of magnitude ($\sim 10^{17}$ fissions). However, due mainly to differences in geometry and moderator, the victim of the UNC accident was more heavily irradiated and received a much larger dose to the pelvic region than to the head.

Table VII summarizes results from five samples submitted for analysis from the UNC accident. Head and pubic hair samples from the heavily irradiated patient exhibited sufficient ^{32}P activity to suggest a massive as well as nonuniform exposure. Sulfur neutron dose to the pelvis was estimated to be ~4600 rads, while the dose to the head appears to be in the region of ~1200 rads.

However, uncertainties concerning the location from which the head hair sample was taken (e.g., back, top, or forelock), make it impossible to establish whether the factor of 4 difference in exposure is due solely to geometry or to self-absorption. If, as has been suggested, the victim was leaning against the tank, the factor of 4 difference between head and pelvic dose emphasizes the asymmetry of the exposure and confirms the fact that he was probably close to the source. Such an interpretation is consistent with clinical observations, as well as testimony of the victim concerning his position at the time of the excursion [14]. The average exposure, based on blood ^{24}Na, has been estimated to be approximately 3 times that sustained by the fatally irradiated victim of the Los Alamos accident [4,13]. Doses delivered to the heads in both cases are probably similar (in the region of ~10,000 rads), and it may be worthwhile to consider that similarities in clinical course may be due to dose distribution rather than to total average dose.

Localized rad doses to the two regions from which samples were taken have been estimated assuming that the fraction of the flux seen by sulfur may be as high as 25 per cent. Total gamma-neutron estimates, assuming a flux-to-dose conversion factor of 2.5×10^{-9} rads/min/cm^2 [13] for the entire neutron spectrum and a gamma-neutron ratio of 2.8 for a moderated homogeneous system, are ~11,400 rads to the head and ~47,000 rads to the pelvis and lower abdomen. These estimates are in good agreement with independent determinations based on blood ^{24}Na [13]. Additional information gained from hair analysis was the confirmation that the system was critical 1-1/2 hours later, when two additional UNC personnel entered the area to drain the tank containing the fissile material. Dose estimates from hair samples indicated small exposures which, while higher than blood ^{24}Na determinations [13], were in the same ratio as indium foil measurements obtained from their dosimeters [14]. Finally, a calculation of total fissions, based on the activation of the pubic hair of the fatally exposed individual, yielded a value of $\sim 1.7 \times 10^{17}$, again in fair agreement with estimates made in other laboratories [15]. Inverse

square calculations of dose are consistent for both the head and pubic hair, assuming a geometry in which the head was 110 cm and the pelvis 42 cm from the excursion.

In the fourth accident mentioned in this report involving significant exposure to personnel at the Hanford Laboratory in 1962 [16], hair dosimetry was also employed. This accident is of particular interest since, contrary to usual circumstances, significant amounts of physical dosimetry data were available and are being reported here in detail by Parker [17]. In this incident, as well as in the others described, nonuniformity of exposure was evident from comparisons of the relative specific activities of hair samples taken from various anatomical locations (e.g., head, back, and pubis).

5. Discussion

Although ^{32}P measurements in hair are admittedly subject to greater uncertainties than more sophisticated dosimetry systems, in general, agreement has been sufficient to provide useful estimates of neutron dose. In controlled experiments, the largest discrepancies tended to occur with very low doses, but the reliable range spans the region of sublethal to supralethal doses of total gamma plus neutron radiation with the additional advantage that, in most cases, a potential victim always has his hair with him. The constant sulfur content of hair indicates that an average value may be substituted for direct sulfur analysis, materially shortening the procedure without appreciably affecting the result. The relatively long half-life of ^{32}P in comparison with ^{24}Na also permits the measurement to be made over a longer period of time than blood ^{24}Na determinations. This fact was evident in the UNC accident, where samples were submitted for analysis two to four weeks after the excursion.

It should be emphasized that in instances where radiation fields are uniform and homogeneous total-body exposures are sustained, the method offers no particular advantage. However, sodium activation yields average doses due to mixing which, under

conditions of partial-body shielding or gross asymmetry of the radiation field such as have been encountered in accidents to date, are of limited value. Under practical conditions, the fixed anatomical location of hair has the distinct advantage of providing a relative estimate of dose distribution.

6. Conclusions

If we can draw conclusions from the limited clinical data available, one salient point is that the Los Alamos and UNC accidents, though not comparable in average dose, are certainly comparable in terms of the dose to the head and thorax. The apparent similarities in clinical course and survival tend to suggest that with doses in the region of 10,000 rads the head and thorax may be the area of limiting sensitivity and that larger or smaller doses to the lower abdomen or extremities do not greatly affect either the clinical course or duration of survival. An extreme example would be a shielded situation in which only the head and thorax are exposed. Under such conditions, blood ^{24}Na values would be relatively low despite the grave prognosis.

The simplicity of the analytical method, the small sample required, and the ready availability of hair suggest induced ^{32}P activity as a biological parameter to be routinely employed in conjunction with blood ^{24}Na measurements for the determination of the neutron doses received by potential nuclear-critical accident victims.

TABLE I. SULFUR AND PHOSPHORUS CONTENT OF HUMAN HAIR

Distribution[a]	No. Samples Analyzed	Sulfur mg/g Mean ± S. D.	Phosphorus mg/g Mean ± S. D.	P/S (per cent)
Head	64	47.1 ± 5.1	0.155 ± 0.042	0.33
Pubis	68	47.3 ± 5.6	0.251 ± 0.065	0.53
All samples (head, chest, abdomen, pubis, legs)	168	47.7 ± 5.5	---	--

[a]All colors of hair are represented; samples are predominantly of caucasoid origin.

TABLE II. SULFUR AND PHOSPHORUS CONTENT OF SAMPLES FROM VARIOUS ANATOMICAL LOCATIONS FROM THE SAME INDIVIDUAL

Anatomical[a] Distribution	Sulfur (mg/g)	Phosphorus (mg/g)	P/S (per cent)
Head	43.2	0.162	0.38
Beard	39.5	0.143	0.36
Chest	43.8	0.185	0.42
Abdomen	46.3	0.158	0.34
Pubis	45.6	0.194	0.43
Leg	46.6	0.153	0.33
Arm	48.7	0.129	0.26
Mean $\pm$ S. D.	44.8 $\pm$ 3.0	0.161 $\pm$ 0.026	0.36

[a]Samples taken and analyzed simultaneously.

TABLE III. COMPARISON OF FIRST COLLISION NEUTRON DOSE ESTIMATES BASED ON HAIR ^{32}PHOSPHORUS MEASUREMENTS AND OTHER PHYSICAL DOSIMETRY

Sample No.	Godiva Neutron Dose (rads)		Kiwi Neutron Dose (rads)[b]	
	Hair ^{32}P	Referee[a]	Hair ^{32}P	Sulfur Pellet
1	23	26	77	61
2	152	165	82	72
3	139	165	8	5
4	31	29	6	8
5	272	311		
6	276	311		
7	456	526		
8	364	404		
9	196	190		
10	185	190		
11	83	80		
12	76	80		

[a] ^{10}B-clad ^{239}Pu, ^{237}Np, ^{238}U, and sulfur pellets, Hurst proportional counter, tissue-equivalent and graphite ionization chambers, and a calibrated fission counter.

[b] $E_n > 2.5$ Mev.

TABLE IV. EXPERIMENTAL DETERMINATION OF INCIDENT NEUTRON DOSE AND ORIENTATION OF A PLASTIC MANNEQUIN EXPOSED TO GODIVA RADIATION

Sample No.	Position		Incident Dose (rads)	
	Actual	Deduced	Hair ^{32}P	Referee[a]
Ia	Pelvis Posterior	Posterior	5	
b	Pelvis Lateral	Lateral	159	
c	Pelvis Lateral	Lateral	150	
d	Pelvis Anterior	Anterior	199	
e	Head Forelock	Head	183	
f	Head Top	Head	170	186
IIa	Head	Facing Assembly	700	
b	Head	Facing Assembly	917	
c	Chest	Facing Assembly	905	
d	Chest	Facing Assembly	989	
e	Pubis	Facing Assembly	834	
f	Axilla	Facing Assembly	837	971

[a]Referee dosimetry represents an average measurement at a single point using the previously mentioned detectors. The detector system and mannequin were placed equidistant from the critical assembly with the detectors at chest height.

TABLE V. FAST NEUTRON FLUX, DOSE, AND POSITION ESTIMATES BASED ON THE RELATIVE SPECIFIC ACTIVITIES OF HAIR SAMPLES FROM THE SL-1 ACCIDENT

Sample	Source	Flux Detected by Sulfur (n/cm^2)	Dose (rads)[a] $E_n > 2.5$ Mev	Deduced Position
IF-1	Head	2.04×10^{12}	7.81×10^{3}	Partially shielded
	Pubis	8.27×10^{9}	0.32×10^{2}	Shielded
IF-2	Head	2.84×10^{13}	1.09×10^{5}	Exposed
	Pubis	4.85×10^{11}	1.86×10^{3}	Partially shielded
IF-3	Head	9.26×10^{12}	3.54×10^{4}	Exposed

[a]Assuming 3.83×10^{-9} rads/n/cm^2.

TABLE VI. DOSE ESTIMATES FROM BLOOD ^{24}SODIUM AND HAIR ^{32}PHOSPHORUS FOLLOWING 1958 LOS ALAMOS CRITICALITY ACCIDENT

Region Exposed and Conditions	Neutron Dose (rads)	Gamma Dose (rads)	Total Dose (rads)
Head, incident	2600	7800	10,400
Thorax, incident	3000	9000	12,000
Pubis, incident	<< 1000	--	--
Total body, ^{24}Na average	900	3000-4000	3900-4900

TABLE VII. FLUX AND DOSE ESTIMATES BASED ON ^{32}PHOSPHORUS MEASUREMENTS FROM WOOD RIVER JUNCTION, UNITED NUCLEAR CORPORATION CRITICALITY

Hair Sample	Hair[a] dis/min/g	Flux Detected by Sulfur (n/cm^2)	Incident Dose (rads)		
			$E_n > 2.5$ Mev[b]	Total[c]	Gamma-Neutron[d]
WRJ-1 Pubis	8990	1.26×10^{12}	4600	12,600	47,000
WRJ-1 Head	2160	3.02×10^{11}	1200	3000	11,400
WRJ-2 Pubis	38	5.32×10^{9}	20	53	200
WRJ-2 Head[e]	12	1.68×10^{9}	6	17	60
WRJ-3 Body[f]	52	7.28×10^{9}	28	73	280

[a]Fractional abundance of sulfur in all samples: 0.05 g/g hair.

[b]Flux-to-dose conversion factor: 3.83×10^{-9} rads/n/cm^2.

[c]Assuming 25 per cent of flux above the sulfur threshold, flux-to-dose conversion factor: 2.5×10^{-9} rads/n/cm^2.

[d]Assuming gamma-neutron ratio of 2.8 from Oak Ridge experiments [13].

[e]Haircut before sample was submitted.

[f]Sample analyzed four weeks after accident.

APPENDIX I

DETAILED PROCEDURE FOR DETERMINATION OF INDUCED ^{32}PHOSPHORUS IN IRRADIATED HAIR. FAST NEUTRON EXPOSURE UNCOMPLICATED BY CONTAMINATION WITH FISSION PRODUCTS

1. Hair samples removed from various anatomic locations (e.g., head, chest, arms, legs, pubis) are washed with detergent, distilled water and ethanol and sucked dry on a Buchner funnel.

2. Samples of approximately 100 mg are accurately weighed and ignited in a Schöniger flask (500-ml) containing 5 ml of 6 $\underline{N}$ HNO_3. After combustion is complete, shake flask vigorously to absorb P_2O_5 and heat to boiling for 1 minute to convert to orthophosphate (see Note 1).

3. Add 2 ml of P carrier and rinse contents into a 40-ml centrifuge tube in minimum volume.

4. Add 10 ml of magnesia mixture and make the solution slightly alkaline by dropwise addition of conc. NH_4OH. Allow to stand 5 minutes with stirring. Add 10 ml conc. NH_4OH and allow to stand with occasional stirring for 1 hour.

5. Filter the precipitate on a tared glass fiber planchet, wash with 1:20 NH_4OH, 50% ethanol, 100% ethanol and suck dry. Allow to equilibrate for 15 minutes in the balance case and weigh as $MgNH_4PO_4 \cdot 6H_2O$. The theoretical yield is 79 mg and chemical yield is calculated directly.

6. The filter disc containing ^{32}P may be counted with any low background system of known efficiency.

7. For a neutron exposure complicated by contamination with fission products, additional chemical decontamination steps must be included.

8. To the sample in a 40-ml centrifuge tube (step 3) add 20 ml of 6 N HNO_3. Warm the solution on a steam bath and add 2 ml Zr carrier to ppt. zirconium phosphate. After heating 3 to 5 minutes centrifuge and discard supernatant. Wash ppt. with water and discard washings (see Note 2).

9. Dissolve ppt. in 0.1 ml conc. HF and add in order: 5 ml of H_2O, 10 ml 6 N HNO_3, 5 drops of 0.1% aerosol solution and 5 ml of ammonium molybdate reagent. Heat the mixture on a steam bath 2 to 5 minutes and centrifuge. Discard supernatant, wash the ppt. with H_2O and discard the washings.

10. Dissolve the precipitate in 0.5 ml conc. NH_4OH, add 10 ml H_2O and 4 drops of 30% H_2O_2 and mix. Add 10 ml conc. HCl, 2 ml Zr carrier and heat on steam bath 5 minutes. Centrifuge and discard the supernatant. Wash the precipitate with H_2O and discard washings.

11. Dissolve ppt. in 0.2 ml conc. HF and add 10 ml of 3 N HCl, 0.5 ml As carrier, and 2 to 3 drops of aerosol solution. Heat 15 minutes on steam bath with constant bubbling of H_2S through the solution. Centrifuge and transfer supernatant to a clean 40-ml centrifuge tube. Wash the ppt. in the original tube with 1 to 2 ml H_2O and 1 to 2 drops of aerosol solution. While washing the ppt., pass H_2S through the original supernatant. Combine the supernatants and discard the As_2S_3 precipitate (see Note 3).

12. Add 2 ml of La carrier to the combined supernatants from the previous step. Centrifuge and transfer the supernatant to a clean 40-ml centrifuge tube. Discard the LaF_3 precipitate.

13. Add 4 ml conc. HNO_3 and 5 ml of ammonium molybdate reagent to the supernatant from the preceding step, heat on steam bath 2 to 5 minutes, centrifuge and discard supernatant. Wash the precipitate with 10 ml of water containing 2 to 3 drops of aerosol and discard washings.

14-17. Alternately repeat steps 10 and 13 twice more.

18. Dissolve the ammonium phosphomolybdate precipitate in 1 ml of conc. NH_4OH and add 2 ml citric acid solution (0.5 g/ml). Add 10 ml of magnesia mixture and conc. NH_4OH dropwise until solution

is just alkaline and then add 10 drops more. Swirl and if ppt. does not form in approximately 1 minute add a few more drops of conc. NH_4OH. After precipitation begins, add 4 ml of conc. NH_4OH and allow to stand 10 minutes with occasional stirring. Filter through a fine sintered glass funnel and wash the precipitate with 1:20 NH_4OH. Dissolve the precipitate in a few drops of conc. HCl and collect the filtrate in a 100-ml beaker.

19. Add 10 ml of magnesia mixture and just enough conc. NH_4OH to neutralize the solution. Add a few drops excess of conc. NH_4OH to initiate precipitation, swirl to mix, and add 3 ml of conc. NH_4OH. Allow to stand for 10 minutes and filter, wash and weigh on a tared glass fiber filter as described in step 5. The counting is as described in step 6. The approximate elapsed time to counting is 6 hours. A brief count is sufficient to assess the gravity of a situation (e.g., A_o = >100 represents an exposure in the lethal range if delivered uniformly).

20. Calculations: the neutron flux above the sulfur threshold is calculated from the expression:

$$F = \frac{A_o W}{\sigma \; s \; N \; \lambda}, \qquad (1)$$

where F is the flux above 2.5 Mev in n/cm^2; A_o is the activity of ^{32}P in dis/min/g hair at T = 0; W is the atomic weight of sulfur in grams (32 g); σ is the activation cross section of sulfur, 225×10^{-27} cm^2/atom; s is the fractional abundance of sulfur in hair; N is Avogadro's number, 6.02×10^{23} atoms; and λ is the decay constant for ^{32}P, 3.38×10^{-5} min^{-1}. Assuming a standard value of 5 per cent for the abundance of sulfur in human hair, the equation becomes:

$$F = 1.4 \times 10^{8} \; A_o. \qquad (2)$$

Flux-to-dose conversion for neutrons with energy in excess of 2.5 Mev determined from the Godiva spectrum is:

$$D_{n \quad 2.5\ Mev} = 3.83 \times 10^{-9}\ F. \qquad (3)$$

However, four accidents involving moderated homogeneous systems [2, 16,18,19] have occurred to date in which the final approximation for the fraction of the flux greater than 2.5 Mev was ~ 25 per cent. Thus, a revision has been suggested by Auxier [13], which may be of general application for homogeneous systems, and becomes:

$$D_{n\ (total)} = 2.2 \times 10^{-9}\ F/0.25, \qquad (4)$$

which may be shortened to:

$$D_{n\ (total)} = 1.23\ A_o. \qquad (5)$$

A second generality which appears to be applicable to accidents involving homogeneous systems derived from the Oak Ridge mockup experiments [2,3] is the assumption of a gamma/neutron ratio of 2.8. The generalized expression for incident total dose to various anatomical locations is given by:

$$D_{n+\gamma} = 3.8\ D_n. \qquad (6)$$

As emphasized in the text of this report, these estimates are designed for rapid assessment of dose and dose distribution for the purpose of establishing a prognosis and course of treatment. In any case, changes in assumptions must be made to fit the specific conditions of the accident and the estimates are always subject to revision contingent on the availability of pertinent data from other sources.

NOTES

1. Larger samples may be ignited in commercially available "Schoniger flasks with expanding gas reservoirs. If time is not limiting, acid digestion as described previously [5] may be employed.

2. In the presence of high concentrations of $SO_4^=$ ion, the precipitation of zirconium phosphate is not complete.

3. In view of the possibility of concentrating significant amounts of arsenic in hair, precipitation of As_2S_3 is considered to be an important step and should not be omitted from the procedure.

Reagents

P carrier: 5 mg P/ml [added as $(NH_4)_2HPO_4$ in H_2O], standardized.

Zr carrier: 10 mg Zr/ml [added as $ZrO(NO_3)_2 \cdot 2H_2O$ in N HNO_3].

As carrier: 10 mg As/ml [added as $Na_2HAsO_4 \cdot 7H_2O$ in H_2O].

La carrier: 10 mg La/ml [added as $La(NO_3)_3 \cdot 6H_2O$ in H_2O].

HCl:3 N and conc.

HNO_3:6 N and conc.

HF:conc.

Citric acid: 500 g/liter, aqueous.

NH_4OH: 1:20 and conc.

H_2O_2: 30% (superoxol).

H_2S: gas.

Ammonium molybdate reagent [200 g $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$, 800 ml H_2O, 160 ml conc. NH_4OH].

Magnesia mixture [50 g $MgCl_2 \cdot 6H_2O$, 100 g NH_4Cl, 3 to 5 drops conc. HCl, 500 ml H_2O].

Aerosol solution: 0.1% aerosol OT in H_2O.

Ethanol: 50% and 95%.

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