HEALTH PHYSICS AND SAFETY DIVISION

EVALUATION OF ACCIDENTAL EXPOSURE TO ACCELERATOR PERSONNEL

Carl H. Distenfeld, Robert D. Colvett and Joseph A. Ash

April 4, 1973

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Informal Report

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EVALUATION OF ACCIDENTAL EXPOSURE TO ACCELERATOR PERSONNEL*

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A B S T R A C T

An accelerator radiation protection program should include means to evaluate accidental exposures. A method relating an accident victim's body activation to his absorbed dose has been developed. The body activation is measured by a simple survey meter or a whole body counter.

A phantom filled with a tissue-equivalent solution, along with several dosimeters, was irradiated in the magnet enclosure of the Alternating Gradient Synchrotron. A calibration graph was prepared relating body activation, as measured by a midchest ion chamber reading, for various irradiation periods and post-irradiation times. The technique is capable of detecting exposures as low as 1 rad within a factor of two.

*Research carried out at Brookhaven National Laboratory under contract with the U. S. Atomic Energy Commission.

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I. INTRODUCTION

Health Physics is concerned with dosimetry under all conditions from routine operations to accidental exposures. Historically, routine dosimetry has been well described for all types of work areas involving ionizing radiation, and accelerator dosimetry programs are no exception.

Accidental exposures and their evaluation have been well described for all major sources of radiation producing equipment, except for high energy accelerators.

Accelerators whose maximum energy capability is less than about 10 to 100 MeV can cause both intensive local damage due to direct beam impingement and whole-body involvement through beam diffusion and scattering. The more usual case for low energy positive ion accelerators is local impingement with the beam.

Positive ion high energy accelerators (above 1 BeV) are characterized by having an envelope of accelerating and experimental apparatus around the beam, limiting local impingement. Furthermore, most of the secondary particles produced by interaction with experimental targets and the envelope equipment are limited to a forward angle of few degrees by high forward momentum. Cascade buildup then takes place in the envelope materials, producing high energy particles which diffuse out. This leads to an accidental exposure condition that is most probably whole body and is unique in radiation composition and energy spectra.

The present work presents one method of quickly evaluating an accident resulting in an exposure under such conditions. The exposed individual, his family, attending physicians, and the health physicist can benefit greatly from an early exposure evaluation. For example, the exposed individual and his family may be put at ease if they can be told the exposure was small enough to preclude sickness, while attending physician may better direct his response, taking the necessary diagnostic tests, etc.

II. METHOD

The method relies on the correlation of body activation as measured by a conventional survey instrument and the dose received. With the aid of the calibration graph (Fig. 5), the exposed individual's dose may be estimated. Furthermore, the method does not rely on any external dosimeters and is useful if the exposed individual is not wearing any dosimeter. However, external dosimeter information is indeed useful in better understanding the nature of the exposure.

III. APPARATUS

In order to permit accurate activation and decay studies, an Alderson Research Man-Phantom containing all the major organs, except for a skeleton, was filled with a tissue-equivalent solution (Table 1) and compounded to include all elements found in a standard man⁽¹⁾ in gram or greater amounts. The phantom itself is made of 9.36 kg of tenite buturate* (essentially carbon and hydrogen). The lungs were not filled to better approximate the true body activation pattern.

The resulting mixture is a slurry due to insolubility; it was impossible to formulate a soluble mixture from the conveniently available stock. Fortunately, the Alderson Man-Phantom used was divided into eleven major

* Eastman Chemical Products, Inc. Trade name for cellulose acetate butyrate.

compartments so that the slurry was proportioned about the entire body in relation to component body weight. The compartments used were the head, upper and lower trunk, upper and lower arm, thigh and lower leg.

The phantom wore the standard BNL film badge containing the usual film packets corrected by aluminum and cadmium filters positioned in the conventional mid-upper chest position. For indication of exposure uniformity a variety of detectors, film badges, high range dosimeters and capsules containing ^6Li and ^7Li TLD phosphors were placed on the head, back, crotch and knee positions. The multiple detectors suggest that the midchest position received a slightly larger exposure, 20% greater than the other positions (Table 2). Because of the presence of a thermal neutron field, gamma and low beta radiations were evaluated by the density of the aluminum filter of the BNL film badge rather than that under the cadmium filter. The unknown detector response to the exposure spectra prevented the acceptance of the above detectors as absolute dose determining instruments.

Direct measurements were made with a neutron tissue-equivalent wall ionization chamber with about 6 mm Schonka plastic walls surrounding a 25 cm³ air filled cavity. Because of the small amount of gas compared to tissue-equivalent plastic, the effect of using air instead of tissue-equivalent gas is believed to be negligible. The dose, as measured by the tissue-equivalent chamber, is taken to be the phantom's whole-body dose. In addition, an integrating pulse discharging ionization chamber (IPDIC)⁽²⁾ containing a 3 mm polyethylene liner surrounding an ethylene cavity was used. Finally, the BNL whole-body counter was used to measure components of longer life.

IV. EXPERIMENT

The Alternating Gradient Synchrotron (AGS) magnet enclosure served as the irradiation facility. The phantom was placed in a near standing position,

80 degrees from the vertical, facing, and about 10 feet from the G-10 Target (Figs. 1 and 2).

Body activation as a measure of absorbed dose is dependent on spectra. Thus the calibration graph can be used only for exposures from spectra similar to that encountered in this experiment. In order to obtain some spectral information, Na, Al and Cl were exposed in various locations in the magnet enclosure (Fig. 3). The $\text{Na}(n,\gamma) {}^{24}\text{Na}$ reaction sensitive to thermal neutrons; the $\text{Al}(n,\alpha) {}^{24}\text{Na}$ reaction sensitive to fast neutrons (6 to 100 MeV), and the $\text{Cl}(n, \text{spallation}) {}^{24}\text{Na}$ sensitive to relativistic neutrons (greater than 100 MeV), indicated the spectra were similar at the locations measured. Table 3 lists the ratio of ${}^{24}\text{Na}$ production from Na and Cl to that produced by the Al. In addition, no consistent change is seen as one proceeds along the ring. Based on some hypothetical spectra⁽³⁾, it is estimated that spectra deviations may introduce a 40% error in the dose determination.

The phantom, tissue-equivalent chamber, and IPDIC were irradiated for a 12-minute period of time, during which 2×10^{14} protons of 30 GeV energy interacted on a beryllium wire target. The tissue-equivalent chamber and IPDIC measured 66 rads and 92 rads, respectively. One would expect a higher response from the IPDIC due to the higher hydrogen content of the polyethylene. Immediately after the irradiation the phantom was removed from the magnet enclosure, positioned horizontally, and its activation and decay characteristics studied with a vibrating reed electrometer survey meter (a Victoreen 440), positioned in the midtrunk position (Fig. 1). All metallic objects were removed from the phantom. Large differences were noticed in both the intensity and decay characteristic after removal of the metal objects. For this reason, all analyses and results were referred to the bare phantom. It

is assumed that any accidental exposure evaluations would be accomplished by first removing all metallic objects. Survey meter readings were started 7 minutes after irradiation and continued for another 43 minutes. The phantom was further analyzed by the Brookhaven Medical Department's whole body counter about 40 hours later.

V. DISCUSSION AND RESULTS

Synchrotron irradiated samples of the previously described tissue-equivalent solution indicate a decay characteristic that can be described by three isotopes. Consideration of possible reactions^(4,5) reveal that ^{15}O , ^{13}N and ^{11}C with respective half-lives of 2, 10.1 and 20.4 minutes, are expected to predominate in the first several hours after the exposure. Gamma scans of the tissue-equivalent fluid support this, since only annihilation radiation is observed for about the first 3 hours. ^{24}Na and ^7Be (15 hour and 54 day half-lives, respectively) activity were observed in separate irradiations of the tissue-equivalent solution after the decay of the shorter lived components. The body activation sensed by the survey meter is assumed to be caused by ^{15}O , ^{13}N and ^{11}C . The time dependence of the activity is given by the sum of the three activation equations. The three exponential components were appropriately weighted as described in the Appendix. The above assumes the phantom (or exposed individual) to be exposed to a constant radiation field. The time between machine pulses (2.4 seconds) is sufficiently frequent for this assumption. In order to support the three component model, a polyethylene jug 18 cm in diameter, 30 cm in length, filled with tissue-equivalent fluid, was irradiated for 17 minutes and the decay characteristics followed with a Victoreen 440. Based on this three component model, calculated decay response was plotted against the Victoreen 440 data (Fig. 5). The agreement between the calculated graph and the data points indicate the three

component model adequately describes the body activation decay characteristics for post exposure times exceeding 10 minutes. The equation should be accurate for shorter post-exposure times, as no shorter half-life materials are believed to be present^(4,5).

Based on the experimental run with the phantom, the tissue-equivalent wall chamber and the Victoreen 440, the calibration graph (Fig. 6) was determined. The Appendix has a full description of this graph. The use of this method is illustrated by the following example:

Suppose an accident victim was exposed for 2.5 minutes. After a five and one-quarter minute delay, a midtrunk Victoreen 440 measurement of 0.1 mR/hr was made. Factor A corresponding to these conditions, as found by the calibration graph (Fig. 6), is 10. Thus, the estimated dose is $10 \times 0.1 = 1$ rad. Intermediate irradiation times (not on the graph) can be obtained by interpolation.

Considering experimental, spectral and depth dose deviations, the dose evaluation as described above estimates the dose within a factor of two.

The longer half-lives of the ^{24}Na and ^7Be products allow extension of the body activation technique for much longer irradiations and post-exposure times. Post-exposure times of days can be monitored by the BNL whole body counter.

^{24}Na is produced primarily by activation of body ^{23}Na through the thermal n,γ reaction, with a thermal cross section of 535 mb⁽⁶⁾. Spallation production of ^{24}Na by heavier elements is negligible compared to the thermal neutron production. As the half-life of the ^{24}Na is relatively large, the total dose is directly proportional to the ^{24}Na activity for short irradiation times.

This can be derived from the activation equation by substituting λt_1 for

$1 - e^{-\lambda t_1}$ where t_1 is the irradiation time. This approximation is valid to 10% accuracy for irradiation times up to 5 hours. Calibration to the tissue-equivalent chamber yields a factor of $\frac{64.1 \text{ rads}}{C}$, where C is the sodium activity in μCi .

^7Be is produced by energetic (above 20 MeV) fission and spallation reactions with a 10 mb cross section. This reaction is much less sensitive than the ^{24}Na indicator and was not observable 40 hours post-irradiation in the Alderson Man-Phantom.

Gamma and minimally ionizing spectral components can be assessed by the BNL film badge density under the aluminum filter calibrated with ^{60}Co irradiation. A comparison of the film results and total exposure, as measured by the tissue-equivalent ion chamber, indicates that 45% of the dose is due to gamma rays and their equivalent (low LET) radiation. The accident victim's dose thus may be crudely estimated as 2.2 times the film badge reading. Similarly, a comparison of the other personnel monitors and the total exposure, as measured by the tissue equivalent ion chamber, all the dosimeters the exposed individual may be wearing, should be considered in estimating his absorbed dose.

VI. CONCLUSION

A technique has been developed to determine accidental exposure of personnel inadvertently exposed in the magnet enclosure of the AGS with the possible exception of the Linac-AGS intersection area*.

Body activation of the man represents the earliest information regarding the exposure and may be measured by standard commercially available ionization chamber instruments. A Victoreen 440 survey meter was used for this work. A dose as low as 1 rad could be determined. The technique should be limited to a quick estimate of the accident victim's dose. Afterwards a detailed investigation by recreating the accident with more sophisticated equipment should be performed to yield a final dose estimate.

Body ^{24}Na , as measured by the BNL whole body counter, can be used to estimate dose resulting from longer exposures and longer post-irradiation

*As the spectra may be different in this area. No foil runs were made in this area.

times. A dose as low as 1 rad can also be determined by this means.

Accidental body dose may be estimated by processing the film badge and assigning an exposure of 2.2 times the value predicted by the density under the aluminum filters.

Exposure evaluation is believed to be within a factor of two.

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FIGURE CAPTIONS

Fig. 1	Phantom Location
Fig. 2	Diagram of Phantom with Dosimeters and Survey Meter
Fig. 3	Locations of the Na, Al and Cl Activation Runs
Fig. 4	Jug Phantom Run
Fig. 5	Calibration Graph

Figure 1
PHANTOM LOCATION

Figure 2

Figure 3

LOCATIONS OF THE Na, Al & Cl ACTIVATION RUNS

Figure 4

JUG PHANTOM RUN

RESPONSE OF VICTOREEN 440
TO IRRADIATED JUG PHANTOM

x = RELATIVE VICTOREEN 440
READING

Figure 5

CALIBRATION GRAPH

TABLE 1
Tissue-Equivalent Solution

<u>Substance</u>	<u>Chemical Formula</u>	<u>Amount (gms)</u>
Calcium Nitrate	$\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$	5,850
Calcium Chloride	CaCl_2	165
Glucose	$\text{C}_6\text{H}_{12}\text{O}_6$	9,000
Potassium Orthophosphate	K_2HPO_4	312
Iron Oxide	Fe_2O_3	5
Water	H_2O	35,388
Sodium Thiosulphate	$\text{Na}_2\text{S}_2\text{O}$	395
Urea	NH_2CONH_2	1,850
Isopropanol	$\text{C}_3\text{H}_8\text{O}$	14,380
Ammonium Orthophosphate	$(\text{NH}_4)_2\text{HPO}_4$	2,570
Zinc Oxide	ZnO	<u>3</u>
Total		69,918

TABLE 2
Personnel Monitoring Information

Bodily Monitors

	<u>Film</u> ¹	<u>TLD 600</u> ²	<u>TLD 700</u> ²	<u>Self Reader</u> ³
HEAD	25 R	950 R	87 R	36 R
CHEST	29 R	970 R	100 R	50 R
CROTCH	34 R		92 R	44 R
KNEE	26 R	1,000 R	90 R	54 R

- Notes:
1. The density of the duPont 1290 film used was determined under the aluminum filter as a ⁶⁰Co like exposure. Exposures were too high for meaningful interpretation of the NTA film.
 2. TLD 600 and 700 were calibrated with ⁶⁰Co radiation. The poor agreement of the TLD 700 is not well understood. The unusually high readings may be attributed to TLD 600 contamination.
 3. 600 R (full scale) Landsverk C.D. pocket ion chamber interpreted as ⁶⁰Co radiation. The chamber is thought to be made of phenolic plastic and assumed to be essentially rad responding, in agreement with the tissue-equivalent wall ionization chamber results of 66 rad.

TABLE 3
²⁴Na Production Ratios

<u>POSITION</u>	<u>Na/A1</u>	<u>Cl/A1</u>
G-5 (O)	3.92	.442
G-8 (O)	7.89	.105
G-10 (O)	5.29	.116
G-11 (O)	5.10	.297
G-12 (O)	1.91	.111
G-15 (O)	7.05	.270
G-20 (O)	2.23	.669
H-5 (O)	5.00	.784
H-15 (O)	4.83	.124
G-8 (I)	2.59	.435
G-11 (I)	6.11	.209
G-20 (I)	3.12	.256
Average $\pm$ Standard Deviation	4.59 $\pm$ 1.98	.318 $\pm$.234

Monitoring positions were along the ring wall approximately 5'6" high, opposite the center of the indicated magnet. The "(O)" and "(I)" signify the outer and inner walls, respectively.

TABLE 4
Target Elements and Products

<u>Target Element</u>	<u>Moles/70 Kg Tissue</u>	<u>Product Isotopes</u>	<u>Gross Section (mb)</u>	<u>a₁</u>
¹⁶ O	2844	¹⁵ O	25	.44
		¹³ N	10	
		¹¹ C	10	
		⁷ Be	10	
¹⁴ N	150	¹³ N	25	.21
		¹¹ C	10	
		⁷ Be	10	
¹² C	1050	¹¹ C	20	.35
		⁷ Be	10	
²³ Na		²⁴ Na	525 (thermal)	
			300 (weighted over 1/E spectrum)	

APPENDIXConstruction of the Calibration Graph

As stated in the text, the three body activation products observed are ^{15}O , ^{13}N and ^{11}C .

Assuming the accident victim to be exposed to a constant radiation field, his body activity is given by

$$B = \phi \sum_{i=1}^3 \left(\sum_j n_i \sigma_{ij} \right) (1 - e^{-\lambda_i t_a}) e^{-\lambda_i t_d} \quad (\text{A } 1)$$

$\lambda_i = \lambda_1$ or λ_2 or λ_3 = the decay constants for ^{15}O , ^{13}N and ^{11}C , respectively.

$n_i \sigma_{ij}$ = the product of the number of atoms and their respective cross sections of body elements that may produce ^{15}O , ^{13}N and ^{24}Na , respectively. These are listed in Table 4.

t_a = the irradiation time

t_d = the post exposure time (the time between removal from the magnet and the survey instrument measurement).

ϕ = the flux (particles/cm sec)

Normalizing, B can be expressed as

$$B = k_o \phi \sum_{i=1}^3 a_i (1 - e^{-\lambda_i t_a}) e^{-\lambda_i t_d} \quad (\text{A } 2)$$

where

$$a_i = \frac{\sum_j n_i \sigma_{ij}}{\sum_i \sum_j n_i \sigma_{ij}} \quad (\text{A } 3)$$

k_o is a constant.

Note: $\sum_{i=1}^3 a_i = 1$

For convenience defining

$$f(t_a t_d) = \sum_{i=1}^3 a_i (1 - e^{-\lambda_i t_a}) e^{-\lambda_i t_d} \quad (\text{A } 4)$$

The saturation activity level is thus

$$B_c = \frac{k_0 B}{f(t_a, t_d)} \quad (A 5)$$

As can be seen from equation A2, flux is proportional to the saturation activity. As the spectra is constant, dose rate is also proportional to the saturation activity

$$D_R = \frac{k_1 B}{f(t_a, t_d)} \quad (A 6)$$

where D_R = dose rate

B = activity

k_1 = constant

The survey meter reading (M) is proportional to activity

$$D_R = \frac{kM}{f(t_a, t_d)} \quad (A 7)$$

The constant k is determined by the experimental run with the phantom, a measurement of the dose delivered to the phantom and survey meter reading at a specified time after the exposure. The dose as determined by the tissue-equivalent ionization chamber was used. From several meter readings at different times post-exposure, an average k of $.32 \pm .01$ was determined.

The total dose is the product of the dose rate and irradiation time.

$$D_T = \frac{kMt_a}{f(t_a, t_d)} \quad (A 8)$$

The calibration graph was constructed by choosing various irradiation times and decay times and calculating the dose corresponding to a meter reading of 1 mR/hr.

$$A = \frac{kt_a}{f(t_a, t_d)} \quad (A 9)$$

$$\text{Thus, } D_T = AM \quad (A 10)$$