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Dose Assessment of an Accidental Exposure At IPNS

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Abstract. Seven different methods were used to estimate the dose rate to a female worker who was accidentally exposed in the neutron PHOENIX beamline at the IPNS. Theoretical and measured entrance dose rates ranged from 550 mrem/min to 2850 mrem/min. Theoretical estimates were based on a Monte Carlo simulation of a spectrum provided by IPNS (Crawford Spectrum). Dose measurements were made with TLDs on phantoms and with ionization chambers in a water phantom. Estimates of the whole body total effective dose equivalent (TEDE) rate ranged from 5.2 mrem/min to 840 mrem/min. Assumed and measured quality factors ranged from 2.6 to 11.8. Cytogenetic analyses of blood samples detected no positive exposure. The recommended TEDE rate was 158 mrem/min. The TEDE was 750 mrem.

INTRODUCTION

On March 17, 1993 an accidental exposure occurred at the Intense Pulsed Neutron Source (IPNS) in the PHOENIX beamline. A user unknowingly spent a few minutes in a direct beam. The user was wearing a Thermoluminescence dosimeter badge, with TLD 600 and 700 chips, at the time of the accident. However, the dosimeter (which read 35 mrem) provided no useful information because it was worn on the lapel and outside the range of the field of the narrow beam (5 cm vertical by 2.5 cm horizontal) which transversed the worker at the height of the umbilicus. Also, the badge had been worn for 17 days previous to the accidental exposure. Preliminary measurements taken near the beam indicated 505 mrem/min (neutrons plus gammas) with a hand-held Health Physics Instrument model HPI 1030 tissue equivalent ion chamber. As a result of this incident, a dose reconstruction program was put in place and a set of measurements were made to characterize the beam dose composition in the PHOENIX line.

DESCRIPTION OF IPNS, THE PHOENIX BEAMLINE AND SUBSEQUENT ACTIONS

The IPNS is a national user facility for the use of neutron-scattering to conduct research on condensed matter. The three principal components of the IPNS are the accelerator, the neutron generator, and the neutron-scattering instruments used for research.

The accelerator system consists of an hydrogen ion source, a 750-kV preaccelerator, a 50-MeV linear accelerator, a 500-MeV rapid-cycling synchrotron, and a transport line between the synchrotron and the IPNS target.

Neutrons are generated by a fission and spallation process in which high-energy protons collide with clad uranium, splitting off neutrons that are slowed down by moderators to the energies required for experiments. As many as twelve horizontal neutron beamlines can be activated simultaneously for experiments to be performed.

The proton beam is pulsed, which minimizes heat production and allows time-of-flight spectroscopic methods to be applied to the efficient use of the pulsed source.

The PHOENIX spectrometer is one of the neutron scattering instruments available at IPNS. Two principal types of experiments are conducted with the neutron-scattering instruments. Neutron-diffraction measurements provide information about the structural arrangement of atomic particles, and inelastic neutron-scattering measurements provide information about the dynamics of molecular systems.

The PHOENIX spectrometer is designed for low-temperature measurement (as low as 0.35 K) of quantum liquids and solids. The instrument can operate either as an inelastic spectrometer, with the use of neutron choppers; or as a diffractometer, with the choppers removed. The principal components of the PHOENIX instrument are the refrigerator and gas handling system, the sample cryostat, the incident neutron beam path, the low- and high-angle scattering flight paths, and the beam stop.

During the IPNS run cycle of March 2-19, 1993, the user was conducting experiments with the PHOENIX spectrometer in the diffraction mode. The user was examining a zeolite sample with helium, deuterium, and neon adsorbed into the pore spaces. Before the experiment was initiated, the Instrument Scientist had been present to change the configuration of the instrument from the inelastic scattering mode to the diffraction mode by removing both the T_0 and E_0 choppers and replacing them with steel collimators that fixed the beam size at approximately 5 cm high x 2.5 cm wide.

After the experimental measurements of the zeolite sample had been completed on Tuesday, March 16, the user allowed the cryostat to warm up overnight to permit access to the sample on Wednesday, March 17. The beam gate remained open during the warm-up period, but was presumably closed when the user made adjustments to the refrigeration system as required by the PHOENIX operating practices. Following standard PHOENIX operating practices, the next step in the experiment was to conduct measurements for two standard samples to verify the instrument calibration. At about 1:30 p.m. on Wednesday, March 17, the user approached the PHOENIX instrument area to prepare for removing the zeolite sample and to place the silicon standard in the sample chamber of the cryostat. Inadvertently neglecting to close the beam gate, the user walked by the beam gate control panel on the way to the control panel for the cryostat refrigerator system. The user did not notice the elevated, distant, red beam gate indicator light indicating that the beam gate was open.

After being in direct beam exposure approximately 5 to 10 minutes, the user realized that the beam gate had not been closed. The user confirmed this fact by checking the beam gate status light located approximately 11 inches from the beam gate control panel, the red light was illuminated. The user immediately walked to the beam gate control panel and closed the beam gate by depressing and holding the black button until the green indicator light illuminated. (1)

Two videotape cameras were used to record the user's reenactment of the unplanned exposure. The videotapes were used later to determine the potential exposure time and the user's body position relative to the beam path.

Observations of the videotaped reenactment indicated that the user was in the beam for approximately 4.75 minutes, the neutron beam was incident from the front of the user and centered on the umbilicus. (2)

METHODS AND RESULTS

Experimental Set Up. Because neither the worker's dosimeter badge nor the measurements taken with portable instruments were useful to estimate the worker's total effective dose equivalent, more comprehensive methods had to be used.

To characterize the beam dose composition in the PHOENIX beamline a set of measurements were made using the following devices:

a) Tissue Equivalent and Magnesium ion chambers in a water phantom.

b) TLD badges placed outside of a water jug and in a male tissue equivalent phantom.

c) TLD chips 600 and 700 inserted in different organs of a female tissue equivalent pnantom.

A Monte Carlo Spectrum of the neutron fluence for the PHOENIX beamline called Crawford Spectrum was provided by IPNS. (2).
Seven methods were used to estimate the dose received by the exposed person. The methods were iterative in that each additional method was an extension of the previous one. The methods are given approximately in the chronology in which they were used. Following is a brief description of these methods.

Method #1

The PHOENIX Crawford Spectrum which is a Monte Carlo simulation for IPNS beamlines was used to estimate the entrance dose equivalent rate. Conversion factors of fluence to dose equivalent from NCRP38 were used to calculate the dose equivalent rate. Table 1 gives the Crawford Spectrum data with the fluence rate, the energy bins and the quality factor for those fluences. The spectrum was also broken in two energy ranges to simplify the calculations. For neutrons with energy lower than 0.1 MeV the average quality factor was 2.6, for neutrons in the energy range $0.1<E< 10$ MeV the average quality factor was 8.5. The average quality factor for the whole spectrum was 4.1. The average quality factors were obtained by dividing the sum of the products of the fluence rate and quality factor (QF) for each energy bin $[F(E_1,E_2)xQF]$ by the total fluence rate $[\Sigma\ F(E_1,E_2)]$ for a selected energy range. Using conversion factors from NCRP 38, dose equivalent rates for the Crawford Spectrum are given in Table 2. It is worth noting that 73.9% of the dose equivalent rate comes from neutrons with energies between 0.1 to 10 MeV while this energy range contributes only 26.6% of the total fluence rate. Based on the data from Table 2 the calculated entrance dose equivalent rate was 2850 mrem/min.

Method #2

Just after the accidental exposure, thermoluminescent dosimeter (TLD) badges placed on a five gallon jug of water were exposed to the beam. The purpose of this measurement was to obtain a physical estimate (in contrast to the calculated one in Method #1) of the entrance dose. A total of six

TLDs badges were deployed outside of the jug of water for 10 minutes, two at the beam height, two below and two above the beam. The TLDs reading in mrem were based on an assumed quality factor of 9.7 (based on calibration with a Pu-Be source). An entrance dose rate of 550 mrem/min was measured at the beam height.

Method #3

To obtain a first quick estimate of the total effective dose equivalent rate received by the worker, TLD badges were exposed for 10 minutes on the front and back of a Rando male tissue equivalent phantom. No TLDs were placed inside the phantom. The measured entrance dose rate was 579 mrem/min and the total effective dose equivalent rate was estimated to be 199.7 mrem/min. A quality factor of 9.7 (based on calibration with a Pu-Be source) was used to obtain TLD results in mrem.

Method #4

To get a better estimate of organ dose rates, TLD chips 600 and 700 were placed in different organs of an Alderson female tissue equivalent phantom. The 600 chips respond both to neutron and gamma rays and the 700 chips respond mainly to gamma rays. The female phantom is a model of the female torso and is arrayed in a set of horizontal slabs. Different organs are contained in the phantom and they extend through several slabs. The phantom was irradiated for 20 minutes in the PHOENIX beamline and was oriented with the beam centered on its umbilicus. This geometry was chosen based on the information given by the exposed worker. In each slab of the phantom the gamma ray (TLD 700) and the neutron (TLD 600 - TLD 700) doses were averaged (sum of the dose divided by the number of TLD chips) for each organ slice. The total organ dose was obtained by summing the individual slab's doses. (Problems with using this method of calculating the total organ doses will be addressed in Method 5). Ten TLD 600 and 700 chips were also inserted in slab #25 (at the height of the umbilicus) but the TLD data was not used in this method.

The total effective dose equivalent rate using the calculated organ doses and the weighting factors from ICRP26 and ICRP60 were 340 mrem/min and 840 mrem/min respectively. In this method the responses of the TLDs were based on a calibration using a Pu-Be source with an assumed quality factor of 9.7. The Pu-Be source has a neutron spectrum that was known to be different from that in the PHOENIX beamline.

Table 1. Average Quality Factors for Crawford Spectrum

Range (MeV) (E_1 - E_2)		$F(E_1, E_2)$ n/cm^2.s	QF (Interpolated values from NCRP 38)		$F(E_1, E_2)$ x QF	QF Average	
<u>$E < 0.1$</u>							
0 - 0.001		2.78×10^6	2		55.6×10^5		
1.0×10^{-3} - 2.15×10^{-3}		2.76×10^5	2		5.52×10^5		
2.15×10^{-3} - 4.64×10^{-3}		2.82×10^5	2		5.64×10^5		
4.64×10^{-3} - 0.01		2.82×10^5	2.5		7.05×10^5	2.6	
0.01 - 0.0215		3.0×10^5	2.5		7.5×10^5		
0.0215 - 0.0464		3.19×10^5	2.5		7.98×10^5		
0.0464 - 0.1		3.8×10^5	7.5		28.5×10^5		
<u>$0.1 \leq E \leq 10$</u>	**Subtotal**	**46.19×10^5**		**Subtotal**	**117.79×10^5**		4.1
0.1 - 0.215		4.66×10^5	7.5		34.95×10^5		
0.215 - 0.464		4.9×10^5	7.5		36.75×10^5		
0.464 - 1.0		3.68×10^5	11		40.48×10^5	8.5	
1.0 - 2.15		2.32×10^5	9		20.86×10^5		
2.15 - 4.64		0.92×10^5	8		4.36×10^5		
4.64 - 10		0.25×10^5	6.5		1.62×10^5		
	Subtotal	**16.73×10^5**		**Subtotal**	**142.02×10^5**		
	Total	**62.92×10^5**		**Total**	**259.81×10^5**		

Table 2. Calculation of Dose Equivalent for Crawford Spectrum from Lagranian Interpolation of NCRP 38

Range (MeV) $(E_1 - E_2)$	$F(E_1, E_2)$ $n/cm^2.s$	$\frac{n}{cm^2.s} / \frac{mrem}{hr}$	mrem/h for $F(E_1, E_2)$	% Total Dose Equivalent
0 - 0.001	2.78×10^6	250	1.112×10^4	6.5
1.0×10^{-3} - 2.15×10^{-3}	2.76×10^5	272	1.015×10^3	0.59
2.15×10^{-3} - 4.64×10^{-3}	2.82×10^5	274.7	1.027×10^3	0.60
4.64×10^{-3} - 0.01	2.82×10^5	275.9	1.044×10^3	0.61
0.01 - 0.0215	3.0×10^5	262.6	1.143×10^3	0.67
0.0215 - 0.0464	3.19×10^5	209	1.526×10^3	0.89
0.0464 - 0.1	3.8×10^5	107	3.551×10^3	2.08
0.1 - 0.215	4.66×10^5	38.3	1.217×10^4	7.12
0.215 - 0.464	4.9×10^5	20.1	2.44×10^4	14.3
0.464 - 1.0	3.68×10^5	45.6	6.571×10^4	38.4
1.0 - 2.15	2.32×10^5	46.7	3.478×10^4	20.3
2.15 - 4.64	0.92×10^5	9	1.022×10^4	5.98
4.64 - 10	0.25×10^5	7	3.571×10^3	2.09
	Total Dose Equivalent Rate	~	2850 mrem/min	

Method #5

The same TLD data obtained from the Alderson female phantom for the method above was used in this calculation. In this method, the TLD data obtained from slab #25, which was at the height of the umbilicus, was of critical importance. A set of 10 TLD chips 600 and 700 were inserted in slab #25, approximately 1 cm apart from each other. These measurements were necessary to determine dose change as a function of depth in the phantom. In conjunction with these measurements another set of depth dose measurements were performed using a 0.05 cm^3 Magnesium Ionization Chamber, which is sensitive only to gammas, and a 0.05 cm^3 Tissue Equivalent Chamber, which is sensitive to neutrons plus gammas, in a 16 cm long water phantom (a cubic water tank). The water phantom was exposed in the beam at the same height of slab #25. Both ion chambers were scanned horizontally through the length (depth) of the water phantom.

The ratio of slab #25 TLD responses in light output to the measurements in rad obtained with the chambers (at the same depth) was plotted as a function of depth. Two curves were generated: ratio of TLD neutron response in light output to Tissue Equivalent Chamber neutron dose in rad, and ratio of TLD gamma response in light output to Magnesium Chamber gamma dose in rad, both as a function of depth. Having the two calibration curves for neutron and gamma response allowed us to relate any TLD response in light output at a particular depth to absorbed dose in rad. This correlation was needed because the PHOENIX Spectrum was known to be very different from the one produced by the Pu-Be source used to calibrate the TLDs. Based on those two calibration plots it was possible to calculate the absorbed dose to a single organ as a function of depth in the phantom.

A key difference between this method and the previous one is that the response of the TLDs (light output) was normalized to measurements made by the ionization chambers and was therefore independent of the TLD's calibration.

In each slab of the phantom the gamma ray (TLD 700) and the neutron (TLD 600 - TLD 700) responses were averaged (sum of dose to dosimeters divided by the number of dosimeters). Another critical difference between this method and the previous one is that the dose to a whole organ was obtained by averaging the average response of the individual slabs.

The quality factor in the PHOENIX beamline was determined for direct beam exposure with a recombination chamber. Direct measurement of QF with a recombination chamber is based on the principle that QF is proportional to the magnitude of ion recombination in an ion chamber. The model REM-2 ionization chamber determines an effective QF by measuring the effect of energy loss (dE/dx) as a function of columnar ion recombination.

The quality factor determination is done by measuring the current at two different voltages. One voltage (1200V) is into the saturation region and the other (65V) is in the initial region of columnar recombination. The average quality factor determined for mixed fields, neutrons plus gammas, is 8.2 ± 25%, the quality factor for neutrons is 11.8 ± 25%.

To confirm the accuracy of the measurements performed with the ionization chambers at the PHOENIX beamline, a set of measurements were performed at Fermilab in the Neutron Therapy Facility where a known dose was delivered. Just as in the PHOENIX beamline a water phantom was scanned horizontally through a depth of 16 cm by the ionization chambers. A known dose was delivered in a geometry similar to the PHOENIX incident. The chambers measured the delivered dose within one percent. Based on this comparison it was clear that the ionization chambers were spectrum independent and were the appropriate device to characterize the dose composition of the PHOENIX beamline.

Using measured quality factor of 8.2 for mixed fields the determined total effective dose equivalent rate to the exposed person was 114 mrem/min based on weighting factors of ICRP26 and was 158 mrem/min based on ICRP60.

It is of interest to compare the dose rate using the measured quality factor with dose rates using quality factors predicted by the Crawford Spectra. Table 3 shows a calculation of TEDE using QF from the Crawford Spectrum as well as the measured ones. If the Crawford Spectrum were only made up of neutrons with energies less than 0.1 MeV the average QF for this energy range would be 2.6 and the TEDE associated to this energy range would be 33.5 mrem/min. On the other hand if the Crawford Spectrum were only made up of neutrons with energy between 0.1 MeV and 10 MeV the average quality factor for this spectrum would be 8.5 and the TEDE associated to it would be 86.1 mrem/min. The average QF for the entire spectrum was estimated to be 4.1 and the TEDE was 46.9 mrem/min.

Method #6

A Monte Carlo neutron photon transport code MCNP (3) was used to calculate the neutron and gamma fluences for organs distributed through the phantom. The results of the simulation was based on the Crawford Spectrum normalized to the measurements performed with the ionization chambers. Those fluences were used to obtain organ dose equivalent and total effective dose equivalents for Crawford Spectrum from the PHOENIX beamline. The total effective dose equivalent rate under ICRP26 guidance was about 5.20 mrem/min.

Table 3. Summary Table Using TLDs Based on ICRP60

Organ or Tissue	Eff.Dose Qn[a]=2.6	Eff.Dose Qn[a]=4.1	Eff.Dose Qn,g[b]=8.2	Eff.Dose Qn[a]=8.5	Eff.Dose Qn[a]=11.8
	(rem/min)	(rem/min)	(rem/min	(rem/min)	(rem/min)
Brain	4.69E-06	4.99E-06	3.58E-05	5.87E-06	6.53E-06
Thyroid	4.92E-05	5.76E-05	3.31E-04	8.20E-05	1.00E-04
Esophagus	4.17E-05	4.87E-05	2.81E-04	6.91E-05	8.45E-05
Thymus	4.76E-06	5.91E-06	2.90E-05	9.27E-06	1.18E-04
Lung	1.75E-04	2.15E-04	1.09E-03	3.31E-04	4.18E-04
Liver	9.62E-04	1.31E-03	4.85E-03	2.32E-03	3.09E-03
Spleen	6.83E-05	9.64E-05	3.15E-04	1.79E-04	2.40E-04
Pancreas	2.00E-04	2.74E-04	9.97E-04	4.89E-04	6.51E-04
Kidney and Adrenals	2.07E-04	2.84E-04	1.03E-03	5.10E-04	6.79E-04
Stomach	1.72E-02	2.33E-02	8.83E-02	4.11E-02	5.44E-02
Skin	1.28E-03	1.87E-03	5.31E-03	3.59E-03	4.89E-03
Small and Large Int.	3.22E-04	4.41E-04	1.60E-03	7.90E-04	1.05E-03
Ovaries	1.19E-02	1.77E-02	4.77E-02	3.45E-02	4.71E-02
Colon	3.69E-04	4.83E-04	2.02E-03	8.18E-04	1.07E-03
Uterus	1.50E-05	1.95E-05	8.34E-05	3.28E-05	4.28E-05
Bladder	1.09E-04	1.37E-04	6.47E-04	2.20E-04	2.82E-04
Breast	9.71E-05	1.21E-04	5.86E-04	1.92E-04	2.44E-04
Eyes					
Bone Marrow	4.25E-04	5.55E-04	2.35E-03	9.38E-04	1.22E-03
Eff.Dose (rem/min)	3.35E-02	4.69E-02	1.58E-01	8.61E-02	1.16E-01

[a] Qn is the quality factor for neutron
[b] Qn,g is the quality factor for a mixed field of neutron and gamma radiation

Method #7

Chromosome analyses of blood samples provided by the exposed worker were performed at Orise-Oak Ridge Laboratory and at Argonne National Laboratory. At Argonne an HPRT analysis was performed in addition to the standard Giemsa analysis.

The data analyzed by both laboratories provided evidence that any dose that the worker might have received was too low to be detected by using standard cytogenetic dosimetry methods. In the cytogenetic analysis, the lower limit of detection for this kind of analysis is around 10 to 20 rem.

DISCUSSIONS AND CONCLUSIONS

Table 4 shows a summary of the measured and calculated entrance dose rates by the different devices for direct beam exposure at the PHOENIX beamline. It is worth noting that the ionization chambers together measured a total dose equivalent rate of 1185 mrem/min for the entrance dose rate. This is roughly a factor of two higher than the dose measured by TLD badges and the HPI-1030 and a factor of 2.4 lower than the value estimated using the results from the Crawford Spectrum.

Table 4. Summary of Measured and Estimated Entrance Dose Rates

Measurement or Calculation	mrad/min	QF	mrem/min
HPI 1030	50.5 (n + γ)	10	505
TLD Badge (Water Phantom)	56.7 (n + γ)	9.7	550
TLD Badge (Rando Phantom)	59.7 (n + γ)	9.7	579
T.E. Ion Chamber	100 (n)	11.8	1180
Mg Ion Chamber	5 (γ)	1	5
Crawford Spectrum (estimated dose)	-	NCRP38/5480.11	2850

Table 5 shows a summary of the Total Effective Dose Equivalent Rate estimated by the different methods. Method three was the first approach in trying to estimate the total effective dose equivalent to the worker. It was known after this measurement that a more refined measurement of the dose to the organs was needed. In Methods 4 and 5 an Alderson female tissue equivalent phantom was used in direct beam exposure with TLD chips inserted in different organs. The results of Method 4 were rejected since inappropriate summing of the slab doses to determine the total organ dose lead to an overestimation of the total effective dose equivalent to the worker.

Table 5. Summary of Total Effective Dose Equivalent Rate Estimated by the Different Methods

Method #	T.E.D.E (mrem/min)
Method #1	N.A.
Method #2	N.A.
Method #3 (ICRP60)	199.7
Method #4 (ICRP26)	340
Method #4 (ICRP60)	840
Method #5 (ICRP26)[a]	114
Method #5 (ICRP60)[a]	158
Method #5 (ICRP60)[b]	46.9
Method #6	5.2
Method #7	N.A.

[a]Based on measured QF of 8.2 for mixed fields
[b]Based on average QF of 4.1 from Crawford Spectrum

The TEDE obtained by the Monte Carlo simulation was rejected because it is orders of magnitude less than any of the measurements. A possible explanation given by Battelle, was that the Crawford Spectrum was biased toward low energy neutrons and the actual spectrum was much harder. It would be difficult to confirm this opinion without performing additional measurements of the neutron spectrum for the PHOENIX beamline.

RECOMMENDED DOSE EQUIVALENT RATE AND DOSE EQUIVALENT

The most defensible method is Method #5 based on ICRP60. ICRP60 was used because a significant amount of the dose was delivered to the skin of the exposed person. ICRP60 has weighting factors for the skin whereas ICRP26 does not. The recommended total effective dose equivalent rate was therefore 158 mrem/min.

Based on the videotapes of the reenactment, it was estimated by viewers that the user was in direct beam exposure for approximately 4.75 minutes, this translates to 750 mrem for TEDE.

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