ANL/ESH-HP-95/01

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DOSE ASSESSMENT OF AN ACCIDENTAL EXPOSURE AT THE IPNS

by

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Dose Assessment of an Accidental Exposure at the IPNS

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Environment, Safety and Health Division

Health Physics Section

February 1995

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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.

Acknowledgments

I would like to thank all my colleagues of the Health Physics Section at Argonne National Laboratory for their immense help in that journey, especially McLouis J. Robinet, Section Head, for his support and encouragement.

Dr. Grdina and Dr. Schawartz for their help in the chromosome analysis and Gordon Homblat for his help in the measurements with the ionization chambers.

Dr. Fun Fong and his staff from ORISE-Oak Ridge for their analysis of blood samples.

From Fermilab-ESH, Dr. Alex Elwyn, Tim Miller, and Fred Krugger who helped me to perform the measurements with the recombination chamber. Also from Fermilab-Neutron Therapy Facility-Dr. Arlene Lennox and all her staff for providing us with the advice and the necessary beam to calibrate our devices.

The IPNS personnel for giving us beam time for two days during these measurements. I am in debt to all of you, your help was immensely appreciated.

Finally, Dr. Robert Wyveen for being so patient with me during the write up of this report, it seems that it took forever but it did not.

This study was a team effort from all those collaborators and laboratories.

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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. (This entire section is an excerpt from Haugen, et al)

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. (See Appendix I for more details.)

The proton beam is pulsed, which minimizes heat production and allows

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 phantom.

A Monte Carlo Spectrum of the neutron fluence for the PHOENIX beamline called Crawford Spectrum was provided by IPNS. (The original spectrum data provided by Crawford is given in Appendix B).

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 A 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 B. 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 B the calculated entrance dose equivalent rate was 2850 mrem/min.

Method #2

Just after the accidental exposure, TLD badges placed on a five gallon jug of water were exposed to the beam (Figure 1). 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, thermoluminescence dosimeter (TLD) badges were exposed for 10 minutes on the front and back of a Rando male tissue equivalent phantom (Figure 2). No TLDs were placed inside the phantom. The measured entrance dose rate was 579 mrem/min and the total effective dose equivalent rate

Table A. 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)		$F(E_1, E_2) \times$ QF	QF Average	
E < 0.1							
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		
0.1 ≤ E ≤ 10	**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 B. Calculation of Dose Equivalent for Crawford Spectrum from Lagrangian 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

Equivalent Total Dose Rate ~ 2850 mrem/min 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. (In Appendix A, details about this calculation are given in the memo from M. J. Robinet to R. Wynveen dated March 23, 1993).

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. (In Appendix F, G details about this calculation are given in memos from R. Toohey to R. Wynveen dated April 26, April 28, 1993).

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 (Figure 4), 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 (Figures 5, 6), 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 (Appendix H, memo from M. Torres to M. J. Robinet dated May 25, 1993 Figure 1).

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 (Figure 7) 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 (Figure 8). 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 $\pm$ 25%, the quality factor for neutrons is 11.8 $\pm$ 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 (Figures 9, 10, 11) 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. (In Appendix H, more information about this calculation).

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 C 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 [MCNP, 1988] 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. (In Appendix J details are given regarding this calculation).

Table C. 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. (More details about those analyses can be found in Appendices C and D).

Discussions and Conclusions

Table D 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 D. 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 E 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 E. 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 (ICRP60)	340
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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MCNP. A general Monte Carlo code for Neutron and Photon Transport. Version 3A. LA 6396-M, Revision 2. September 1986, MCNP 3B Newsletter, July 1988.

Figure 1. TLD Badges Attached to Jug of Water in Beamline

Figure 2. Rando Male Phantom

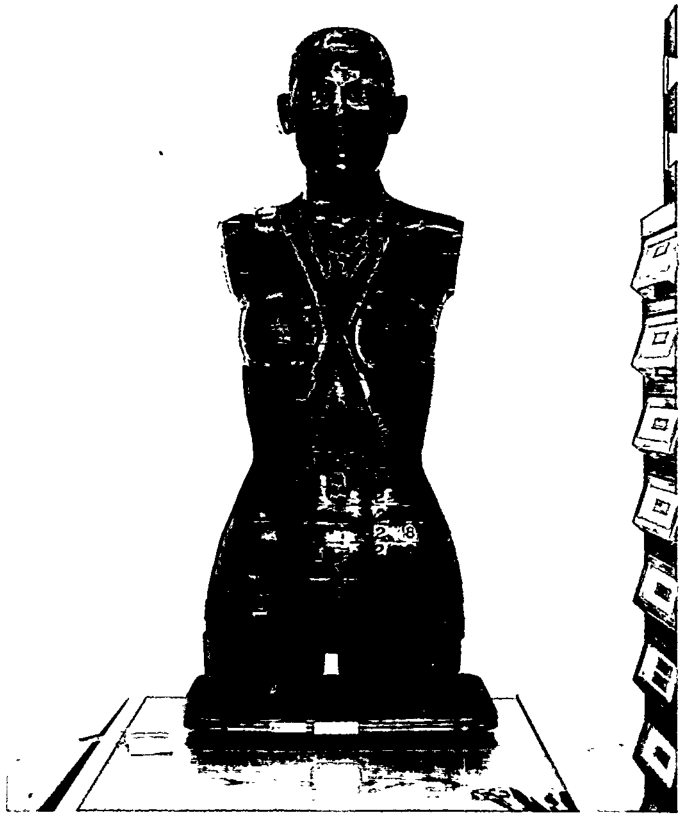

Figure 3. Alderson Female Phantom

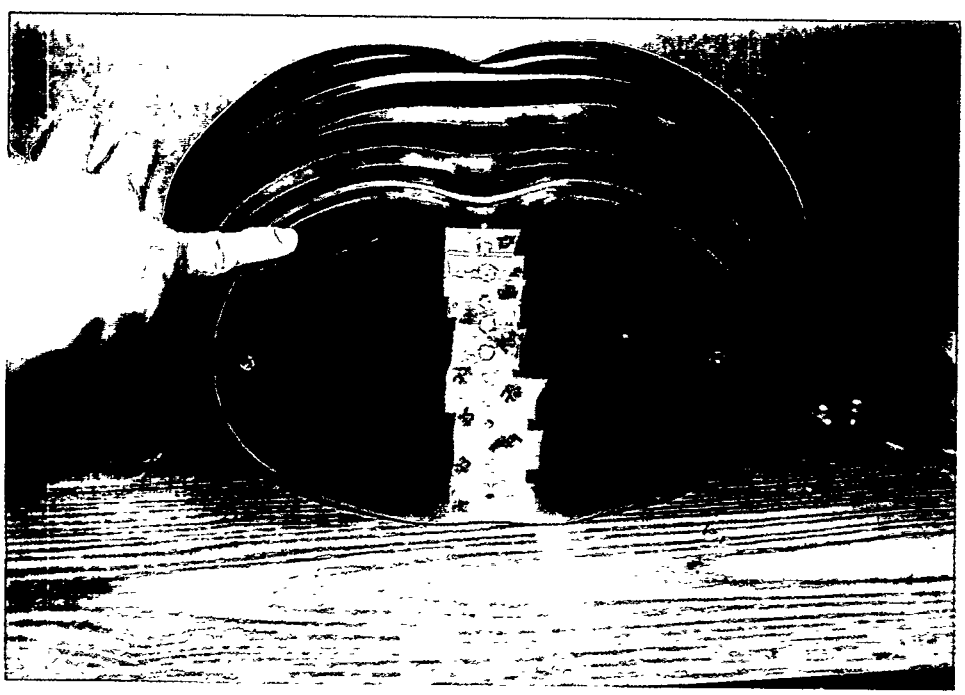

Figure 4. Slab #25 of Alderson Phantom with TLD Chips Inserted on it

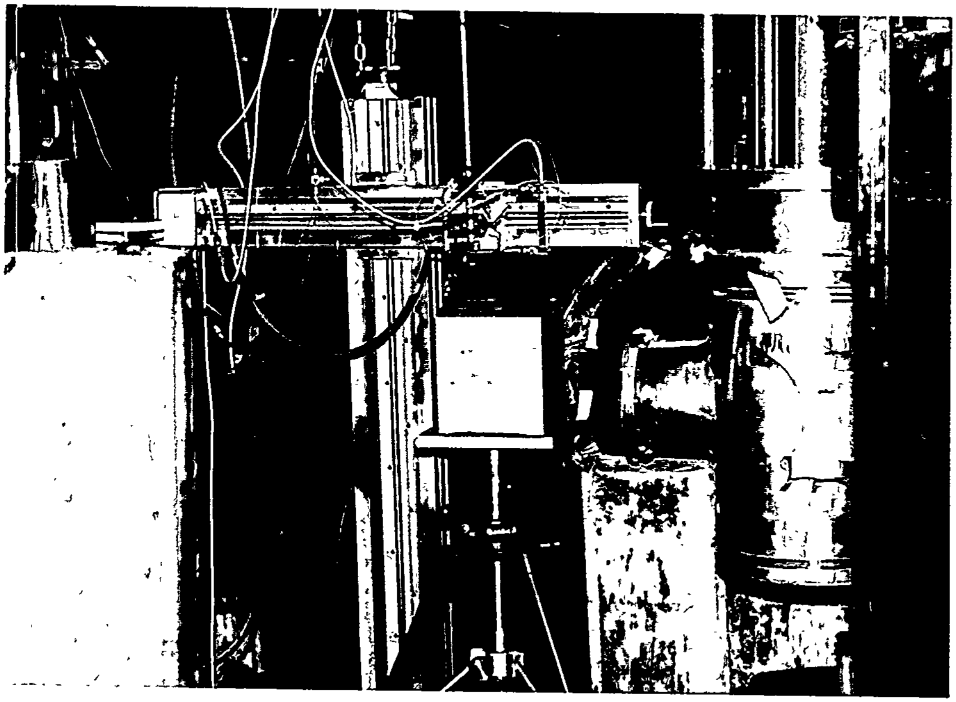

Figure 5. Ionization Chamber Scanning the 16 cm Long
Water Phantom

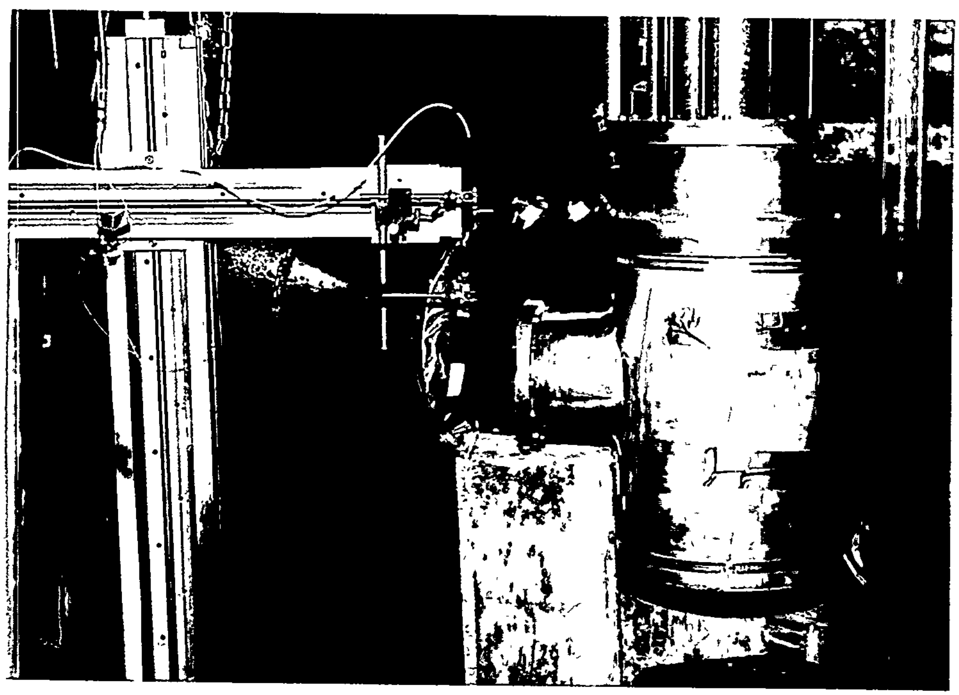

Figure 6. Ionization Chamber with Water Phantom Removed

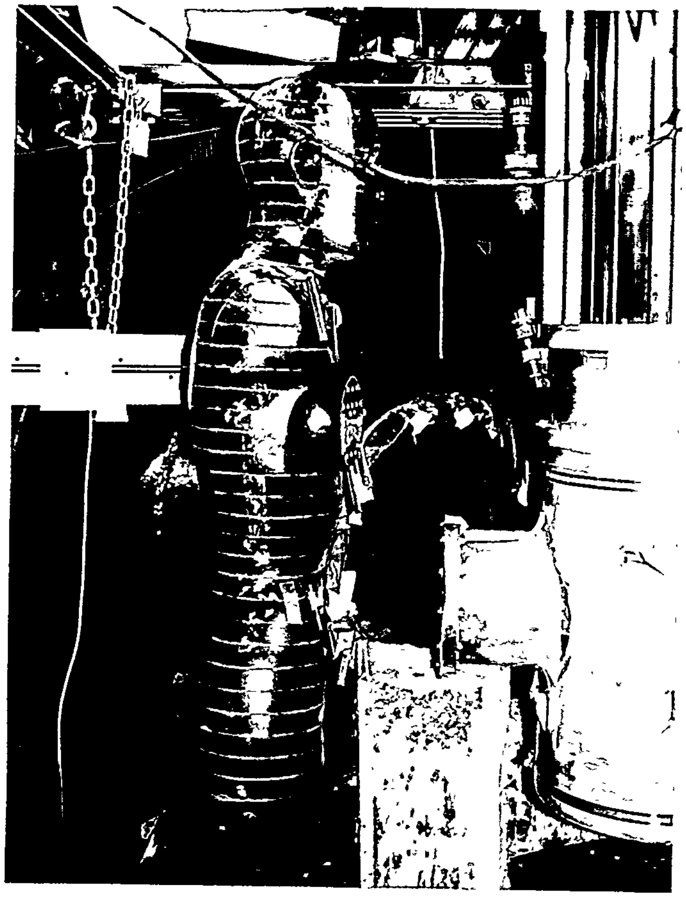

Figure 7. Alderson Phantom in Direct Beam Exposure at the Phoenix Beam

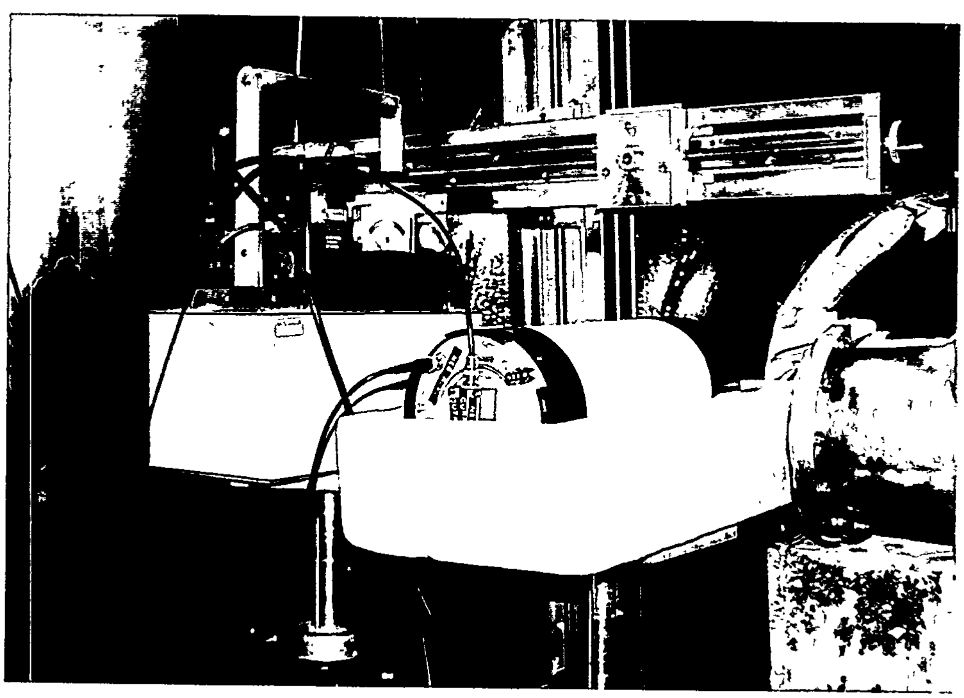

Figure 8. Recombination Chamber

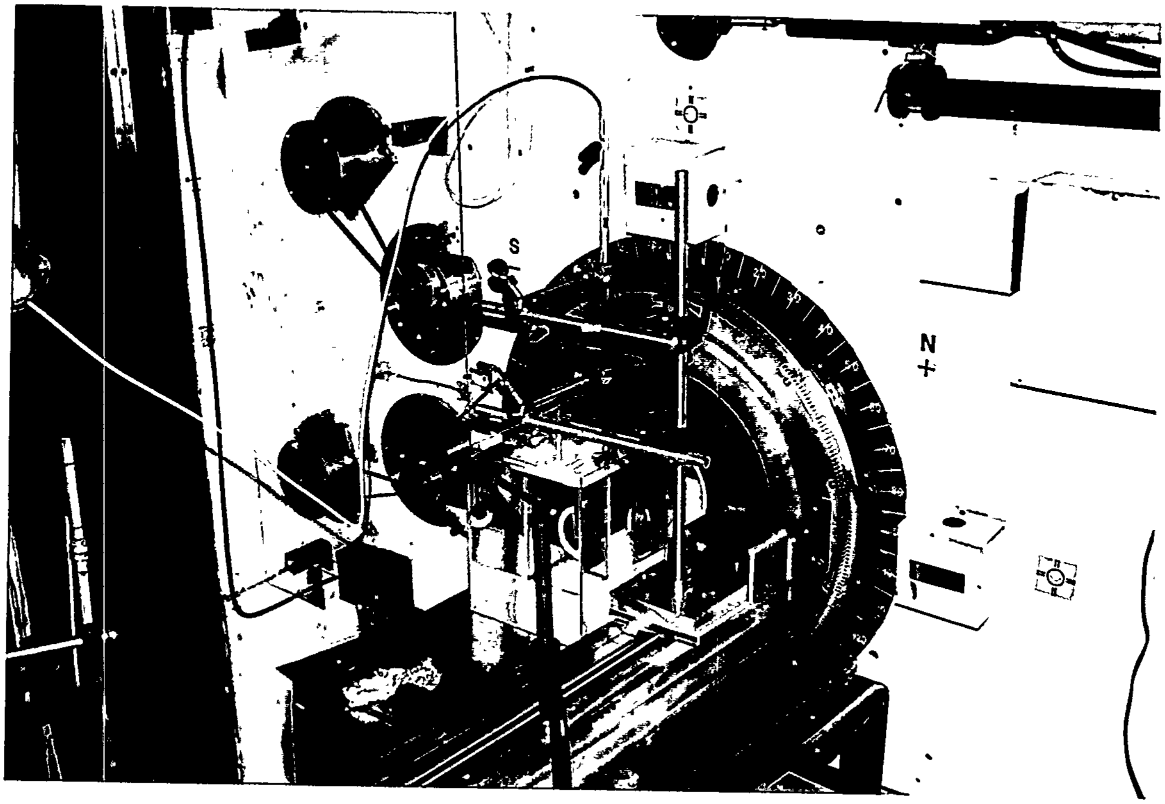

Figure 9. Fermilab Neutron Therapy Facility

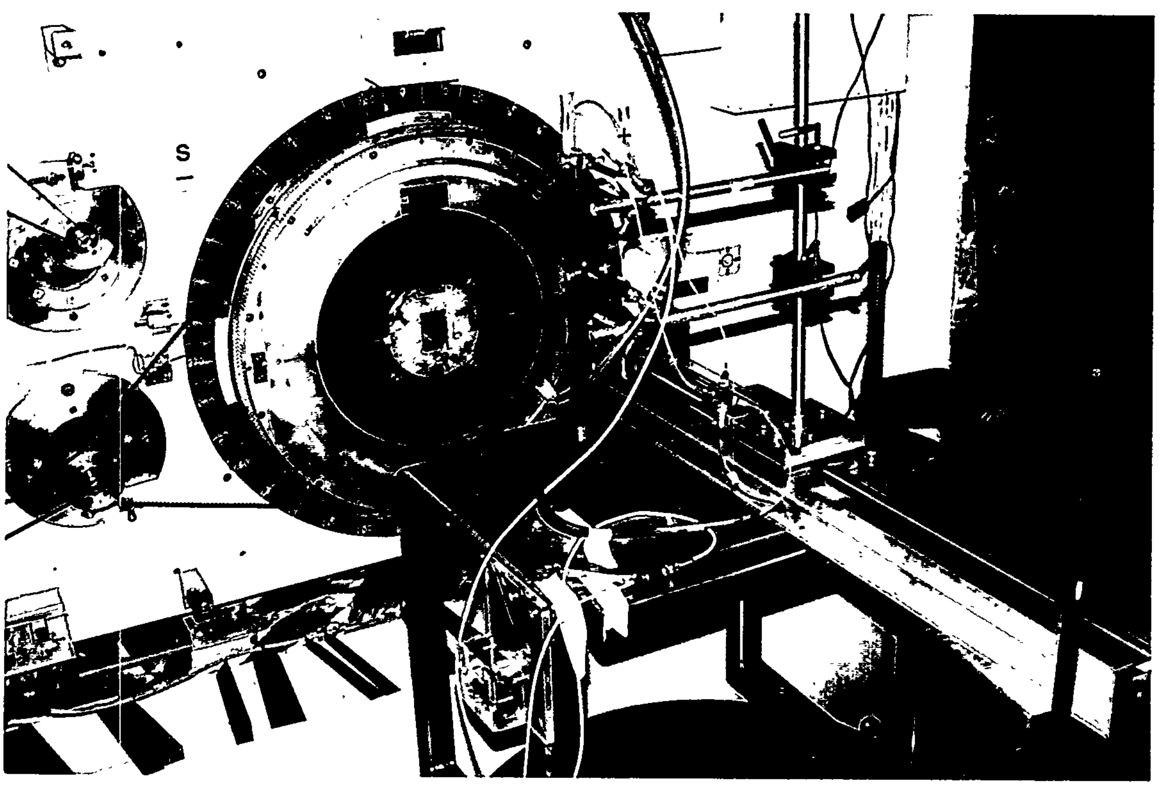

Figure 10. Fermilab Neutron Therapy Facility

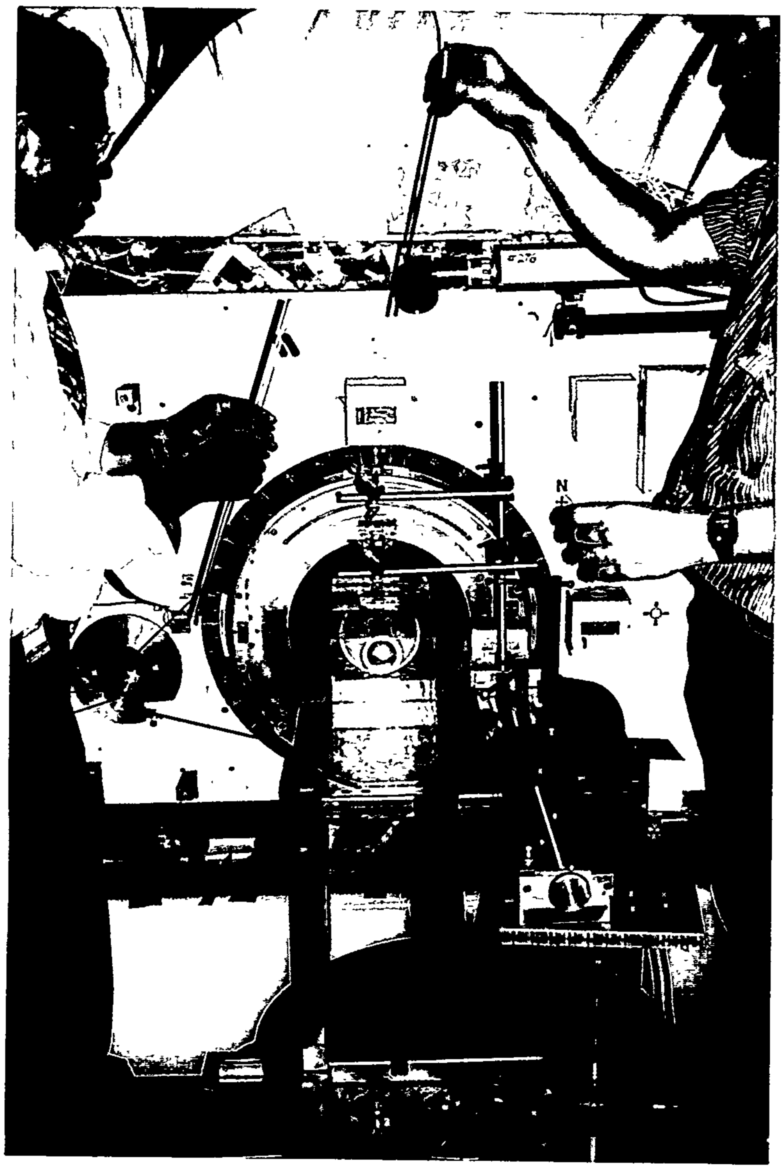

Figure 11. Fermilab Neutron Therapy Facility

APPENDIX A

Memo from M. J. Robinet to R. A. Wynveen dated March 23, 1993

ARGONNE
NATIONAL
LABORATORY

INTRA-LABORATORY MEMO

March 23, 1993

To: R. A. Wynveen Director, ESH

From: M. J. Robinet Section Head, ESH-HP

Subject: **Status and Recommendations on Dose Estimate for Person Exposed in IPNS Neutron Beam - March 17, 1993**

Status of Dose Estimate

Thermoluminescent dosimeters (TLD) were exposed on the front and back of a RANDO tissue equivalent phantom to obtain an estimate of the dose received by . (the exposed person). The measured dose was for an assumed 10 minute exposure (Ms. estimate of the total time she was in the beam). To date we have the following data:

- The entrance dose in the beam (2 inch x 1 inch size) was approximately 6 rem (see Table 1).

- Essentially all of the dose was absorbed within the body (see back doses in Table 1).

- Applying ICRP 60 weighting factors for the different organs and tissue, the worst case whole body effective dose is approximately 2 rem (see Figure 1 and Table 2).

Recommendations

- An attempt should be made to obtain a better estimate of the time interval that was actually in the beam. She should be requested to return to Argonne to reenact her actions while she was being exposed so that a time-motion study could be done.

  The TLD wore on her lapel when she was in the beam read 35 mrem. Using this data point, the initial idea was to eliminate the need for the exposure time by taking the ratio of lapel dose (35 mrem) to that of the phantom's lapel dose (10 mrem) times the phantom's direct beam dose (5791 mrem) to obtain direct beam dose. However, this idea was later rejected because of the uncertainty of movements while she was in the beam area.

- The depth dose (the dose at different depths) in a phantom should be measured to obtain a better estimate of the effective dose. The worst case estimate of the effective dose is based on the assumption that the energy was deposited evenly across the width (front to back) of the body and in equal amounts to all of the organs of interest. The data in Table 1 show that this was probably not what actually happened. The majority of the dose may have been deposited in the first few cm of tissue. If this were true, the dose to organs off the beam center line and near the back of the body may have been much smaller than assumed so that the whole body effective dose would be reduced.

- The neutron spectra in beam line F1 should be remeasured to obtain a better estimate of the neutron quality factor.
- Consider using chromosome aberration dosimetry to obtain a definitive upper limit on the dose actually received.

MJR/cs

cc: R. A. Schlenker
E. Dolecek
M. Torres

Table 1. DATA FROM TLD'S ON RANDO PHANTOM IN IPNS F1 BEAM LINE

		FRONT					BACK		
Badge #	Run #	γ mrem	neutron mrem	Total Average mrem	Badge #	Run #	γ mrem	neutron mrem	Total Averag e mrem
20	1	< 5	10	10	21	1	< 5	< 10	<10
22 (28)‡	1 (2)	<5 (<5)	65 (65)	65	23 (29)	1 (2)	<5 (<5)	<10 (<10)	<10
24 (30)	1 (2)	450 (395)	5810 (4925)	5791*	25 (31)	1 (2)	100 (25)	<10 (30)	<100*
26 (32)	1 (2)	30 (30)	670 (615)	673	27 (33)	1 (2)	<5 (<5)	<10 (<10)	<10

‡ The numbers in parenthesis are for the second run
* Directly in the beam

Table 2. DOSE ESTIMATE BASED ON 10 MINUTE EXPOSURE TIME

Organs or Tissue	Dose (mrem)	Weighting Factor	Effective Dose (mrem)
Brain (R)	0	0.005	0
Thymus(R)	10	0.005	0.05
Thyroid	10	0.05	0.05
Esophagus	10	0.05	0.05
Breast	65	0.05	3.25
Lung	65	0.5 x 0.12	3.9
Lung	5791	0.5 x 0.12	347.46
Stomach	5791	0.12	694.80
Bladder	5791	0.05	289.50
Liver	5791	0.05	289.50
Adrenals (R)	5791	0.005	28.95
Kidney (R)	5791	0.005	28.95
Pancreas (R)	5791	0.005	28.95
Spleen (R)	5791	0.005	28.95
Small Intestines (R)	5791	0.005	28.95
Gonads	673	0.20	134.60
Colon	673	0.12	80.76
Large Intestines (R)	673	0.005	.3.37
Uterus (R)	673	0.005	3.37
Muscle (R)	0	0.005	0
Bone Surface	0	0.01	0

Total Effective Dose 1996.8 mrem

3/23/93

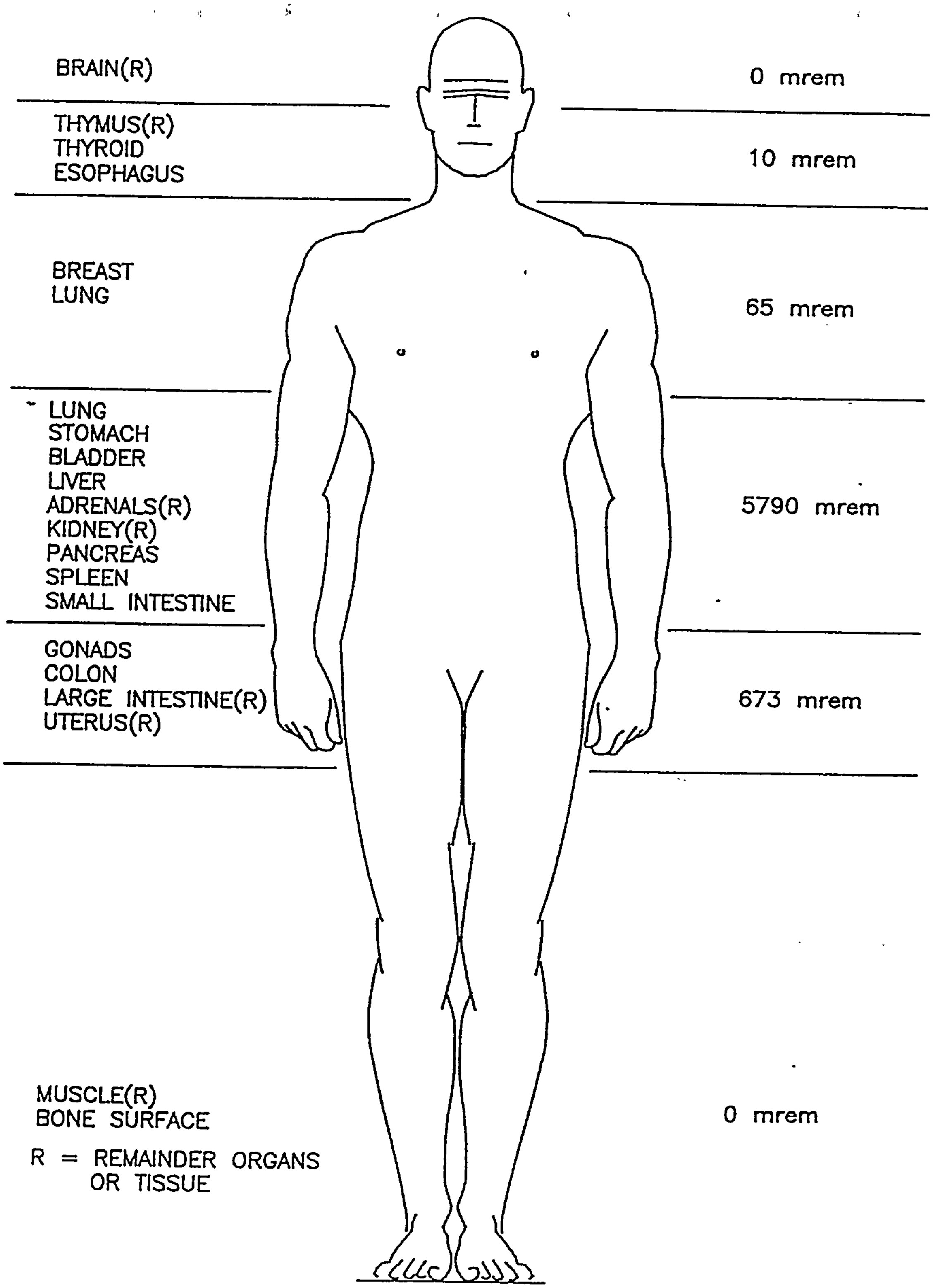

Figure 1. Estimate of Dose to Different Organs and Tissue
(10 minute exposure of RANDO phantom in IPNS Beam line F1)

APPENDIX B

Memo from R. K. Crawford to W. Ruzicka dated April 7, 1993

ARGONNE
NATIONAL
LABORATORY

Intra-Laboratory Memo

Post-It™ brand fax transmittal memo 7671	# of pages ▸ 4
To Mac Robinet	From Bill Ruzicka
Co.	Co.
Dept.	Phone #
Fax #	Fax #

April 7, 1993

TO: **W. Ruzicka**
FROM: **R. K. Crawford** RKC
RE: **Estimated neutron flux in the PHOENIX beamline**

The attached calculations of neutron fluence rates were prepared at the request of M. Robinet, as forwarded by you to me. Please review these notes, and if they are sufficiently clear and comprehensive, please forward them to M. Robinet.

Estimated Neutron Fluence Rates in the PHOENIX Beamline

R. K. Crawford -- April 7, 1993

The IPNS target/moderator geometry has been modeled in the Monte Carlo calculations described in ANL-78-88. These calculations were based on the use of 800 MeV protons (appropriate to the IPNS-II proposed at that time) rather than the 450 MeV protons used at the present IPNS, but in other resepcts represent the present IPNS rather well. Moderators were assumed to be polyethylene rather than the present liquid methane, but hydrogen densities are nearly the same in the two materials, so this difference should be unimportant for neutron energies above 1 eV. The calculated spectra for the different moderator positions are shown in Fig. 40 of ANL-78-88 (page 126), which is reproduced here. The calculated time-averaged neutron beam currents I(E) (neutrons per unit solid angle per unit energy per unit time, integrated over the entire moderator face) are presented in the figure in terms of EI(E) normalized to a single source neutron. Curves A_1 and A_2 of this figure are for the F moderator position.

In order to place the calculated spectra on an absolute scale appropriate to the present IPNS, we make use of the value of EI(E) at 1 eV measured for IPNS. This measurement, reported in ANL-82-80 (page 84), determined that EI(E) for the F moderator was ~3×10^{10} n/sr/sec/μA. This measurement was made with a polyethylene moderator in the F position, and was made on beamline F5. However, calculations and other measurements indicate that the neutron beam currents should be nearly the same for all beamlines viewing the F moderator, and as noted above, there should be little difference between polyethylene and liquid methane for neutron energies above 1 eV.

The flux Φ(E) of neutrons in the beamline at a distance L from the moderator is then given by

$$\Phi(E) = \frac{1}{E}\,\frac{1}{L^2}\,[EI(E)_{meas}]\Big|_{1\ eV} \left(\frac{EI(E)_{calc}}{[EI(E)_{calc}]\Big|_{1\ eV}} \right) \qquad (1)$$

which for the F moderator at IPNS, and using $EI(E)_{calc}$ from curve A_2 of the figure, becomes

$$\Phi(E) = \frac{3 \times 10^{10}}{E\,L^2} \left(\frac{EI(E)_{calc}}{2.3 \times 10^{-4}} \right) \qquad (2)$$

The neutron fluence rate $F(E_1,E_2)$ for the neutron energy interval E_1 to E_2 is then

$$F(E_1,E_2) = \int_{E_1}^{E_2} \Phi(E)\, dE \qquad (3)$$

The A_2 spectrum in the figure has been used in Eqs. (1-3) to estimate the fluence rates for a number of energy intervals for the F1 beamline (the PHOENIX instrument). These estimated fluence rates are shown in Table I, as are the total fluence rates $F(0,E_2)$ for neutrons with energies below E_2. The calculated values for F in the Table are based on a distance L = 14 m (~40 cm beyond the PHOENIX sample position) from the moderator, and on a proton beam current of 12 μA. These values for F can easily be scaled to other distances by multiplying by the ratio $14^2/L^2$, and can be scaled to other proton beam currents by multiplying by the ratio of the proton currents. Accuracies of these values are probably 20-30 %.

Table I -- Estimated Neutron Beam Fluence Rates for the PHOENIX Beamline

E(eV)	$[EI(E)_{calc}]^a$	E_1(eV)	E_2(eV)	$F(E_1,E_2)^b$	$F(0,E_2)$
			1.00		0.92×10^6 [c]
1.47	2.4×10^{-4}	1.00	2.15	1.47×10^5	1.07
3.16	2.6	2.15	4.64	1.59	1.22
6.81	2.8	4.64	10.0	1.72	1.40
14.7	3.0	10.0	21.5	1.84	1.58
31.6	3.3	21.5	46.4	2.02	1.78
68.1	3.6	46.4	100	2.21	2.00
147	3.9	100	215	2.39	2.24
316	4.3	215	464	2.64	2.51
681	4.4	464	1,000	2.70	2.78
1,470	4.5	1,000	2,150	2.76	3.05
3,160	4.6	2,150	4,640	2.82	3.33
6,810	4.7	4,640	10,000	2.88	3.62
14,700	4.9	10,000	21,500	3.00	3.92
31,600	5.2	21,500	46,400	3.19	4.24
68,100	6.2	46,400	100,000	3.80	4.62
147,000	7.6	100,000	215,000	4.66	5.09
316,000	8.0	215,000	464,000	4.90	5.58
681,000	6.0	464,000	1,000,000	3.68	5.95
1,470,000	3.8	1,000,000	2,150,000	2.33	6.18
3,160,000	1.5	2,150,000	4,640,000	0.92	6.27
6,810,000	0.4	4,640,000	10,000,000	0.25	6.30

a Taken from curve A_2 of the figure.

b Because of the way the energy intervals were chosen, this column is just 6.1293×10^8 times the corresponding $[EI(E)_{calc}]$ values of column 2. Units are neutrons/cm^2-sec.

c Estimated using approximate data for a liquid methane moderator scaled to the measured EI(E) at 1 eV.

The calculations only extend up to neutron energies of 10 MeV, but there are very few neutrons in the beam at energies above 10 MeV.

References

ANL-78-88. "IPNS, a National Facility for Condensed Matter Research", Argonne National Laboratory Report ANL-78-88 (1978).

ANL-82-80 J. M. Carpenter, C. W. Potts, and G. H. Lander. "Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (ANL): A Status Report as of June 1982", Proceedings of the 6th Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-VI), Argonne National Laboratory Report ANL-82-80, pp 77-101 (1982).

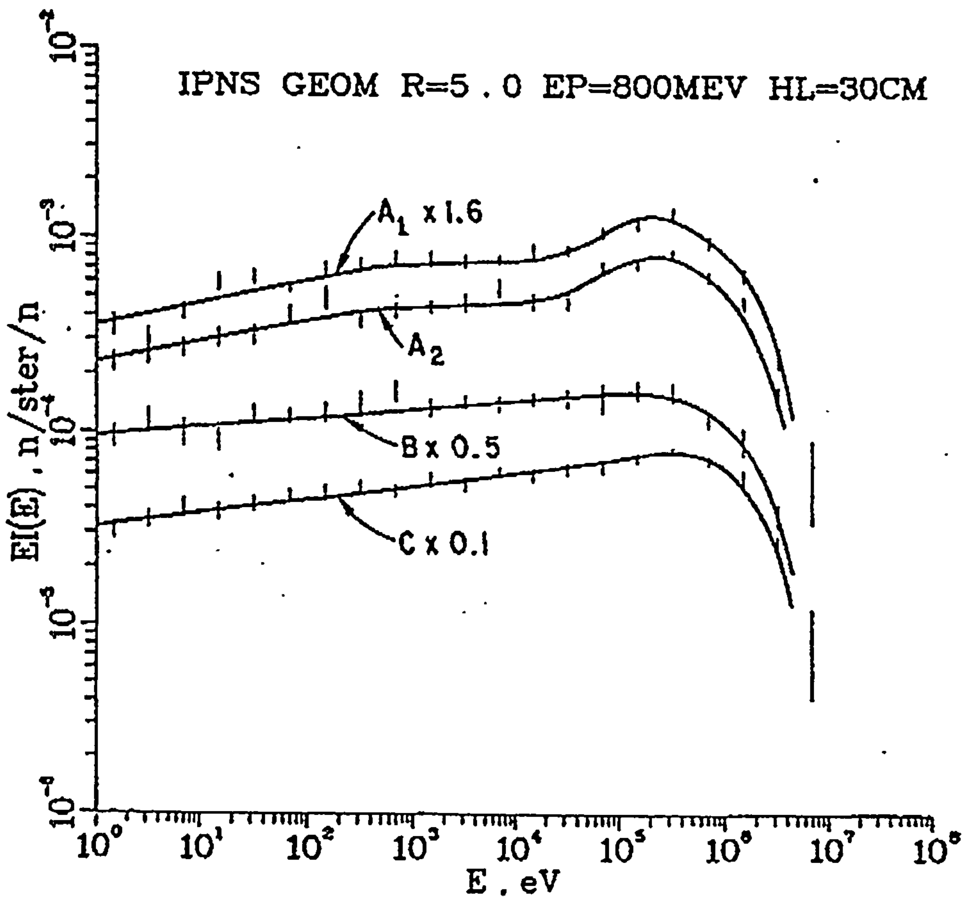

Fig. 40. Beam-current Spectra Computed for IPNS Moderators, for a 10-cm-dia Uranium Target and for 800-MeV Protons

APPENDIX C

Letter from Fun H. Fong to Francis W. Strehl dated April 8, 1993

ORISE
OAK RIDGE INSTITUTE FOR SCIENCE AND EDUCATION
MEDICAL SCIENCES DIVISION

April 8, 1993

Francis W. Strehl, M.D.
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Dear Dr. Strehl:

RE: REAC/TS CASE NO. 1420

Per your request, I am forwarding cytogenetics results to you by fax and by first class mail. Lymphocyte culture and analysis was performed without complication. Usually in individuals with only background exposures, there is an average of 1 dicentric in 500 metaphases observed; however, in case, there were no background chromosomal aberrations observed, either. Our laboratory was not able to distinguish her cytogenetics results from individuals who have no radiation exposures. If you need any other assistance in counselling on her cytogenetics results, please do not hesitate to ask.

Sincerely,

Fun H. Fong, Jr., M.D., FACEP
Director, Radiation Medicine

cc: Dr. Fry
Dr. Littlefield
Dr. Ricks

CYTOGENETICS REAC/TS PATIENT REPORT

TO: Dr. Shirley Fry DATE: April 7, 1993

Copies to: Drs. Fong, Ricks, and Berger; A. Sipe; G. Joiner; RRF; File

SUBJECT NAME: REAC/TS ACCIDENT # 1420.001

Referring Physician: F.W. Strehl, M.D. Address/Telephone Argonne National Laboratory, Argonne, IL 60439 (708) 252-2811

Site of Sample Collection: ORAU ___ Other Argonne, IL

Sample Transit: Via Federal Express Transit Time ~20 hr Culture Date 03/29/93

Exposure Data:

Subject was accidentally exposed for about 10 min to a 10 KeV (90%) neutron beam (1" x 2"). A lapel dosimeter read 35 mrem. Phantom studies were conducted which estimated an entrance dose of 6 rem.

Culture Data:

Blood samples from arrived March 30, 1993, in good condition. Her white blood count was 5,789 per mm. Lymphocyte cultures harvested at 48 hr yielded excellent growth. Slide preparations were stained with fluorescence plus Giemsa blood stain for evaluation of radiation-induced chromosome aberrations in first-division metaphases.

RESULTS AND COMMENTS ON CYTOGENETIC ANALYSES

#Metaphases Scored	# Dicentrics Observed	Dicentric/ Cell	Dose* Estimate	90% Confidence Interval
500	0	0	0	

Comments: We have completed cytogenetic evaluations of lymphocyte cultures initiated from blood samples from . We did not observe any dicentric chromosomes in the 500 1st division metaphases that were evaluated for radiation-induced chromosome aberrations. In our large database of cultures from persons who have had no exposures other than background, we have observed on average 1 dicentric per 500 cells scored. Thus, our findings in : lymphocyte cultures are indistinguishable from data that we would expect to see in persons having no radiation exposures. Thus, our data provide evidence that any localized dose she may have received was too low to be detected using standard cytogenetic dosimetry assays.

L. Gayle Littlefield, Ph.D.

APPENDIX D

Memo from David J. Grdina to M. J. Robinet dated April 15, 1993

References

G. Burger, A. Morhart, P.S. Nagarajan, A. Wittmann. Conversion Functions for Primary and Operational Quantities in Neutron Radiation Protection. Proceedings from the Fourth Symposium on Neutron Dosimetry. Munich-Neuherberg, Ger.; 1981.

R. S. Caswell and J. J. Coyne. Kerma factors for neutron energies below 30 MeV. Radiation Research 83: 217-254; 1980.

Cross, W. G.; H. Ing. Quality factors for monoenergetic neutrons. Radiation Research 99: 1-19; 1984.

International Commission on Radiation Units and Measurements. Determination of dose equivalents resulting from external radiation sources. Bethesda, MD:ICRU; Report 39; 1985.

International Commission on Radiation Units and Measurements. Determination of dose equivalents from external radiation sources - Part 2. Bethesda, MD:ICRU; Report 43; 1988.

International Commission on Radiological Protection. Recommendations of the International Commission on Radiological Protection. Oxford:Pergamon Press; Publication 26; 1977.

R. Kramer; M. Zankl; G. Williams; G. Drexler, The calculation of dose from external photon exposures using reference human phantoms and Monte Carlo methods. Part I: The male (Adam) and female (EVA) adult mathematical phantoms. Münich, GSF-Bericht S-885; December 1982.

MCNP - A General Monte Carlo Code for Neutron and Photon Transport. Version 3A. LA-6396-M, Revision 2. September 1986, MCNP3B Newsletter July 1988.

Appendix A. Crawford Neutron Spectrum for IPNS PHOENIX Beamline.

708 968-3994 home

252-7769 office

Estimated Neutron Fluence Rates in the PHOENIX Beamline

R. K. Crawford -- April 7, 1993

The IPNS target/moderator geometry has been modeled in the Monte Carlo calculations described in ANL-78-88. These calculations were based on the use of 800 MeV protons (appropriate to the IPNS-II proposed at that time) rather than the 450 MeV protons used at the present IPNS, but in other resepcts represent the present IPNS rather well. Moderators were assumed to be polyethylene rather than the present liquid methane, but hydrogen densities are nearly the same in the two materials, so this difference should be unimportant for neutron energies above 1 eV. The calculated spectra for the different moderator positions are shown in Fig. 40 of ANL-78-88 (page 126), which is reproduced here. The calculated time-averaged neutron beam currents I(E) (neutrons per unit solid angle per unit energy per unit time, integrated over the entire moderator face) are presented in the figure in terms of EI(E) normalized to a single source neutron. Curves A_1 and A_2 of this figure are for the F moderator position.

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The flux $\Phi(E)$ of neutrons in the beamline at a distance L from the moderator is then given by

$$\Phi(E) = \frac{1}{E}\,\frac{1}{L^2}\,[EI(E)_{meas}]\Big|_{1\ eV}\left(\frac{EI(E)_{calc}}{[EI(E)_{calc}]\big|_{1\ eV}}\right) \qquad (1)$$

which for the F moderator at IPNS, and using $EI(E)_{calc}$ from curve A_2 of the figure, becomes

$$\Phi(E) = \frac{3\times10^{10}}{E\,L^2}\left(\frac{EI(E)_{calc}}{2.3\times10^{-4}}\right) \qquad (2)$$

The neutron fluence rate $F(E_1,E_2)$ for the neutron energy interval E_1 to E_2 is then

$$F(E_1,E_2) = \int_{E_1}^{E_2} \Phi(E)\,dE \qquad (3)$$

The A_2 spectrum in the figure has been used in Eqs. (1-3) to estimate the fluence rates for a number of energy intervals for the F1 beamline (the PHOENIX instrument). These estimated fluence rates are shown in Table I, as are the total fluence rates $F(0,E_2)$ for neutrons with energies below E_2. The calculated values for F in the Table are based on a distance L = 14 m (~40 cm beyond the PHOENIX sample position) from the moderator, and on a proton beam current of 12 μA. These values for F can easily be scaled to other distances by multiplying by the ratio $14^2/L^2$, and can be scaled to other proton beam currents by multiplying by the ratio of the proton currents. Accuracies of these values are probably 20-30 %.

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E(eV)	$[EI(E)_{calc}]^a$	E_1(eV)	E_2(eV)	$F(E_1,E_2)^b$	$F(0,E_2)$
			1.00		0.92×10^6 [c]
1.47	2.4×10^{-4}	1.00	2.15	1.47×10^5	1.07
3.16	2.6	2.15	4.64	1.59	1.22
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14.7	3.0	10.0	21.5	1.84	1.58
31.6	3.3	21.5	46.4	2.02	1.78
68.1	3.6	46.4	100	2.21	2.00
147	3.9	100	215	2.39	2.24
316	4.3	215	464	2.64	2.51
681	4.4	464	1,000	2.70	2.78
1,470	4.5	1,000	2,150	2.76	3.05
3,160	4.6	2,150	4,640	2.82	3.33
6,810	4.7	4,640	10,000	2.88	3.62
14,700	4.9	10,000	21,500	3.00	3.92
31,600	5.2	21,500	46,400	3.19	4.24
68,100	6.2	46,400	100,000	3.80	4.62
147,000	7.6	100,000	215,000	4.66	5.09
316,000	8.0	215,000	464,000	4.90	5.58
681,000	6.0	464,000	1,000,000	3.68	5.95
1,470,000	3.8	1,000,000	2,150,000	2.33	6.18
3,160,000	1.5	2,150,000	4,640,000	0.92	6.27
6,810,000	0.4	4,640,000	10,000,000	0.25	6.30

a Taken from curve A_2 of the figure.

b Because of the way the energy intervals were chosen, this column is just 6.1293×10^8 times the corresponding $[EI(E)_{calc}]$ values of column 2. Units are neutrons/cm^2-sec.

c Estimated using approximate data for a liquid methane moderator scaled to the measured EI(E) at 1 eV.

The calculations only extend up to neutron energies of 10 MeV, but there are very few neutrons in the beam at energies above 10 MeV.

References

ANL-78-88. "IPNS, a National Facility for Condensed Matter Research", Argonne National Laboratory Report ANL-78-88 (1978).

ANL-82-80 J. M. Carpenter, C. W. Potts, and G. H. Lander. "Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (ANL): A Status Report as of June 1982", Proceedings of the 6th Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-VI), Argonne National Laboratory Report ANL-82-80, pp 77-101 (1982).

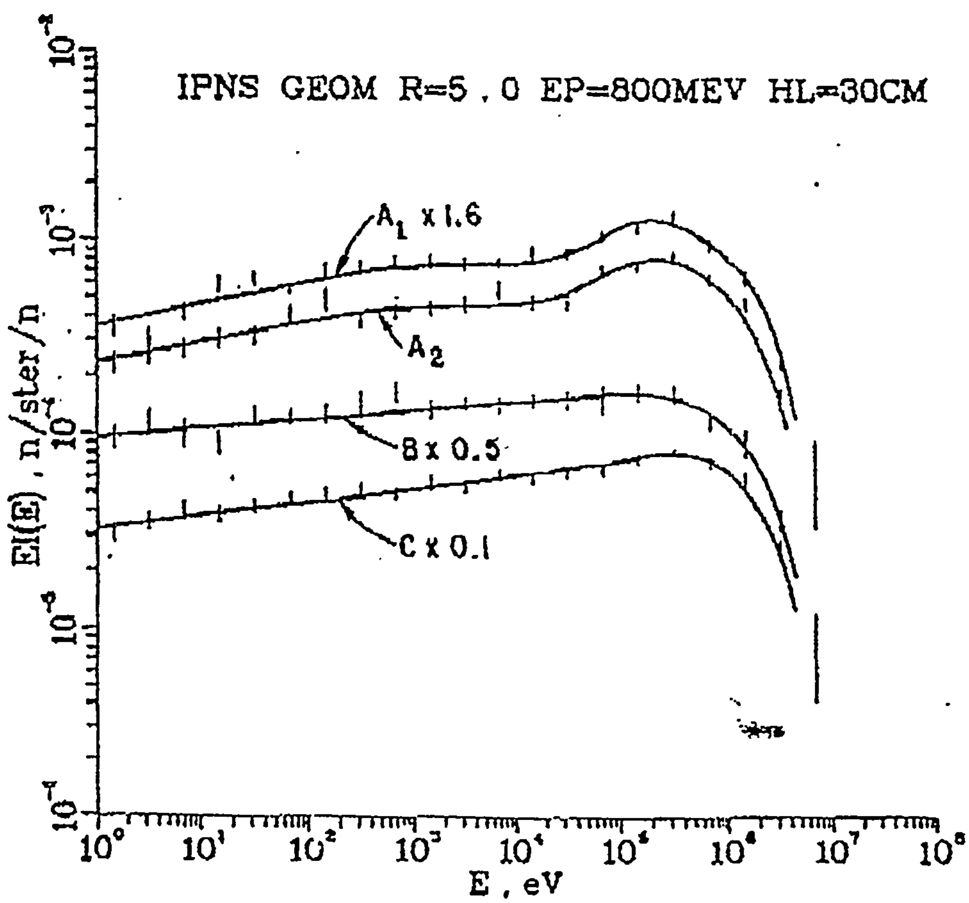

Fig. 40. Beam-current Spectra Computed for IPNS Moderators, for a 10-cm-dia Uranium Target and for 800-MeV Protons

Appendix B. Neutron Dose Rates for Crawford Spectrum

PROGRAM TABULATE v. 1.4
RELEASE DATE: MAY 6th, 1993

R.D. Stewart
Battelle Pacific Northwest Laboratory
Richland, WA 99352
phone: (509) 375-2024
fax: (509) 375-2636
Internet: rd_stewart@ccmail.pnl.gov

MCNP VERSION 3B3
OUTPUT FILE CREATION DATE WED MAY 5 13:46:35

PHANTOM TYPE: Female
WEIGHT FACTORS: Female
SOURCE NORMALIZATION (i.e., beam area): 12.90
AVERAGE ENERGY OF SPECTRUM (MeV): 0.225
INCIDENT NEUTRON DIRECTION:
  Azimuthal Angle (deg): 90.0
  Polar Angle (deg): 180.0

RUN-TIME STATISTICS:
  Particle Histories Executed: 1000000.
  Total Execution Time (min) 694.92
  Particles Per Minute: 1439.0150

Table 1. Summary of Organ Fluences and Average Energies

ORGAN	NEUTRON FLUENCE (CM^{-2})	PERCENT ERROR	AVERAGE ENERGY (keV)	PHOTON FLUENCE (CM^{-2})	PERCENT ERROR	AVERAGE ENERGY (keV)
Lung	1.677E+02	9.090E+00	4.935E+01	2.043E+03	1.020E+00	1.209E+03
Liver	9.316E+03	1.450E+00	1.094E+01	8.866E+03	6.800E-01	1.392E+03
Stomach	2.506E+04	1.580E+00	9.549E+00	1.315E+04	9.200E-01	1.519E+03
Small Intestine	1.999E+05	3.600E-01	6.345E+01	3.706E+04	4.200E-01	1.691E+03
Upper Large	2.099E+05	4.300E-01	8.393E+01	3.691E+04	4.900E-01	1.705E+03
Lower Large	2.126E+04	1.610E+00	1.135E+01	1.185E+04	9.100E-01	1.440E+03
Ovaries	2.687E+04	3.460E+00	1.599E+01	1.620E+04	2.070E+00	1.471E+03
Thyroid	0.000E+00	0.000E+00	0.000E+00	2.937E+02	1.339E+01	1.457E+03
Bone Surface	1.932E+03	1.070E+00	2.751E+02	2.320E+03	5.000E-01	1.346E+03
Trunk	3.120E+04	1.600E-01	4.998E+01	7.711E+03	3.000E-01	1.535E+03
Kidneys	9.074E+03	2.470E+00	5.696E+01	9.892E+03	9.600E-01	1.378E+03
Bladder	5.835E+03	3.970E+00	1.086E+01	8.208E+03	1.240E+00	1.362E+03
Spleen	2.943E+03	5.890E+00	3.233E+01	6.536E+03	1.630E+00	1.283E+03
Pancreas	1.088E+04	3.700E+00	1.188E+01	1.060E+04	1.620E+00	1.377E+03
Thymus	1.756E+01	9.577E+01	1.535E-02	7.664E+02	8.590E+00	1.174E+03
Adrenal	1.986E+03	1.151E+01	4.971E+01	6.789E+03	2.780E+00	1.302E+03
Heart	2.841E+02	1.488E+01	4.241E+01	2.869E+03	1.740E+00	1.134E+03
Brain	0.000E+00	0.000E+00	0.000E+00	1.279E+02	5.750E+00	1.265E+03
Breasts	6.693E+02	5.050E+00	3.198E+01	2.007E+03	1.460E+00	1.369E+03
Uterus	4.301E+04	1.930E+00	1.098E+01	1.962E+04	1.090E+00	1.509E+03
Red Marrow	5.289E+03	3.306E+00	2.298E+02	5.038E+03	1.836E+00	1.370E+03
Skin	1.185E+04	1.000E-01	1.307E+02	3.806E+03	3.000E-01	1.597E+03
Eye Lens	0.000E+00	0.000E+00	0.000E+00	1.667E+02	2.619E+01	8.056E+02

Table 2. Summary of Organ Kermas (absorbed dose)

NOTE: Associated errors are same as errors in fluence (i.e., application of pt. kernels is exact).

ORGAN	NEUTRON KERMA (mrad/min)	PHOTON KERMA (mrad/min)	TOTAL KERMA (mrad/min)	PERCENT ERROR
Lung	1.785E-03	1.240E-01	1.258E-01	1.014E+00
Liver	2.673E-02	6.116E-01	6.383E-01	6.543E-01
Stomach	6.397E-02	9.831E-01	1.047E+00	8.692E-01
Small Intestine	2.647E+00	3.062E+00	5.709E+00	2.804E-01
Upper Large	3.557E+00	3.069E+00	6.626E+00	3.237E-01
Lower Large	6.464E-02	8.445E-01	9.092E-01	8.530E-01
Ovaries	1.008E-01	1.173E+00	1.274E+00	1.926E+00
Thyroid	0.000E+00	1.967E-02	1.967E-02	1.339E+01
Bone Surface	5.291E-02	1.503E-01	2.032E-01	4.630E-01
Trunk	4.180E-01	5.825E-01	1.001E+00	1.870E-01
Kidneys	1.035E-01	6.740E-01	7.775E-01	8.948E-01
Bladder	1.637E-02	5.537E-01	5.701E-01	1.210E+00
Spleen	2.159E-02	4.163E-01	4.379E-01	1.577E+00
Pancreas	3.499E-02	7.188E-01	7.538E-01	1.554E+00
Thymus	3.516E-06	4.554E-02	4.554E-02	8.589E+00
Adrenal	2.130E-02	4.334E-01	4.547E-01	2.704E+00
Heart	2.324E-03	1.644E-01	1.667E-01	1.728E+00
Brain	0.000E+00	8.100E-03	8.100E-03	5.750E+00
Breasts	5.819E-03	1.377E-01	1.435E-01	1.416E+00
Uterus	1.238E-01	1.459E+00	1.583E+00	1.016E+00
Red Marrow	1.929E-01	3.397E-01	5.326E-01	1.675E+00
Skin	4.340E-01	2.995E-01	7.335E-01	1.360E-01
Eye Lens	0.000E+00	7.745E-03	7.745E-03	2.619E+01

Table 3. Summary of Organ Dose Equivalents

NOTE: Average Quality factors are weighted by the dose equivalent. Also, photon dose equivalent = photon kerma (i.e., QF = 1).

ORGAN	NEUTRON DOSE EQ. (mrem/min)	AVERAGE ENERGY (Mev)	AVERAGE QF	TOTAL DOSE EQ. (mrem/min)	WT FACTOR
Lung	1.842E-02	1.537E+00	1.068E+01	1.424E-01	1.000E-01
Liver	2.859E-01	1.169E+00	1.107E+01	8.975E-01	0.000E+00
Stomach	6.862E-01	1.142E+00	1.113E+01	1.669E+00	5.200E-02
Small Intestine	2.712E+01	1.624E+00	1.072E+01	3.018E+01	5.200E-02
Upper Large	3.611E+01	1.708E+00	1.063E+01	3.918E+01	5.200E-02
Lower Large	6.963E-01	1.125E+00	1.116E+01	1.541E+00	5.200E-02
Ovaries	1.058E+00	1.335E+00	1.097E+01	2.231E+00	2.100E-01
Thyroid	0.000E+00	0.000E+00	0.000E+00	1.967E-02	4.000E-02
Bone Surface	4.729E-01	2.909E+00	9.433E+00	6.232E-01	3.000E-02
Trunk	4.538E+00	1.122E+00	1.129E+01	5.121E+00	5.200E-02
Kidneys	1.037E+00	1.737E+00	1.048E+01	1.711E+00	0.000E+00
Bladder	1.742E-01	1.178E+00	1.104E+01	7.279E-01	0.000E+00
Spleen	2.207E-01	1.442E+00	1.054E+01	6.370E-01	0.000E+00
Pancreas	3.778E-01	1.121E+00	1.111E+01	1.097E+00	0.000E+00
Thymus	3.735E-05	1.123E-05	1.091E+01	4.558E-02	0.000E+00
Adrenal	2.165E-01	1.623E+00	1.048E+01	6.500E-01	0.000E+00
Heart	2.405E-02	1.815E+00	1.090E+01	1.884E-01	0.000E+00
Brain	0.000E+00	0.000E+00	0.000E+00	8.100E-03	0.000E+00
Breasts	6.364E-02	1.065E+00	1.138E+01	2.014E-01	2.600E-01
Uterus	1.330E+00	1.161E+00	1.116E+01	2.789E+00	0.000E+00
Red Marrow	1.747E+00	2.759E+00	9.559E+00	2.087E+00	1.000E-01
Skin	4.813E+00	1.012E+00	1.150E+01	5.113E+00	0.000E+00
Eye Lens	0.000E+00	0.000E+00	0.000E+00	7.745E-03	0.000E+00
TOTAL					1.000E+00

EFFECTIVE DOSE EQUIVALENT (mrem/min): 4.80 (0.03)

Appendix C. Neutron Dose Rates for Crawford Spectrum Normalized to the Ion Chamber Measurments.

PROGRAM TABULATE v. 1.4
RELEASE DATE: MAY 6th, 1993

R.D. Stewart
Battelle Pacific Northwest Laboratory
Richland, WA 99352
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fax: (509) 375-2636
Internet: rd_stewart@ccmail.pnl.gov

MCNP VERSION 3B3
OUTPUT FILE CREATION DATE WED MAY 5 13:46:35

PHANTOM TYPE: Female
WEIGHT FACTORS: Female
SOURCE NORMALIZATION (i.e., beam area): 12.90
AVERAGE ENERGY OF SPECTRUM (MeV): 0.225
INCIDENT NEUTRON DIRECTION:
  Azimuthal Angle (deg): 90.0
  Polar Angle (deg): 180.0

RUN-TIME STATISTICS:
  Particle Histories Executed: 1000000.
  Total Execution Time (min) 694.92
  Particles Per Minute: 1439.0150

Table 1. Summary of Organ Fluences and Average Energies

ORGAN	NEUTRON FLUENCE (CM^{-2})	PERCENT ERROR	AVERAGE ENERGY (keV)	PHOTON FLUENCE (CM^{-2})	PERCENT ERROR	AVERAGE ENERGY (keV)
Lung	1.677E+02	9.090E+00	4.935E+01	2.043E+03	1.020E+00	1.209E+03
Liver	9.316E+03	1.450E+00	1.094E+01	8.866E+03	6.800E-01	1.392E+03
Stomach	2.506E+04	1.580E+00	9.549E+00	1.315E+04	9.200E-01	1.519E+03
Small Intestine	1.999E+05	3.600E-01	6.345E+01	3.706E+04	4.200E-01	1.691E+03
Upper Large	2.099E+05	4.300E-01	8.393E+01	3.691E+04	4.900E-01	1.705E+03
Lower Large	2.126E+04	1.610E+00	1.135E+01	1.185E+04	9.100E-01	1.440E+03
Ovaries	2.687E+04	3.460E+00	1.599E+01	1.620E+04	2.070E+00	1.471E+03
Thyroid	0.000E+00	0.000E+00	0.000E+00	2.937E+02	1.339E+01	1.457E+03
Bone Surface	1.932E+03	1.070E+00	2.751E+02	2.320E+03	5.000E-01	1.346E+03
Trunk	3.120E+04	1.600E-01	4.998E+01	7.711E+03	3.000E-01	1.535E+03
Kidneys	9.074E+03	2.470E+00	5.696E+01	9.892E+03	9.600E-01	1.378E+03
Bladder	5.835E+03	3.970E+00	1.086E+01	8.208E+03	1.240E+00	1.362E+03
Spleen	2.943E+03	5.890E+00	3.233E+01	6.536E+03	1.630E+00	1.283E+03
Pancreas	1.088E+04	3.700E+00	1.188E+01	1.060E+04	1.620E+00	1.377E+03
Thymus	1.756E+01	9.577E+01	1.535E-02	7.664E+02	8.590E+00	1.174E+03
Adrenal	1.986E+03	1.151E+01	4.971E+01	6.789E+03	2.780E+00	1.302E+03
Heart	2.841E+02	1.488E+01	4.241E+01	2.869E+03	1.740E+00	1.134E+03
Brain	0.000E+00	0.000E+00	0.000E+00	1.279E+02	5.750E+00	1.265E+03
Breasts	6.693E+02	5.050E+00	3.198E+01	2.007E+03	1.460E+00	1.369E+03
Uterus	4.301E+04	1.930E+00	1.098E+01	1.962E+04	1.090E+00	1.509E+03
Red Marrow	5.289E+03	3.306E+00	2.298E+02	5.038E+03	1.836E+00	1.370E+03
Skin	1.185E+04	1.000E-01	1.307E+02	3.806E+03	3.000E-01	1.597E+03
Eye Lens	0.000E+00	0.000E+00	0.000E+00	1.667E+02	2.619E+01	8.056E+02

Table 2. Summary of Organ Kermas (absorbed dose)

NOTE: Associated errors are same as errors in fluence (i.e., application of pt. kernels is exact).

ORGAN	NEUTRON KERMA (mrad/min)	PHOTON KERMA (mrad/min)	TOTAL KERMA (mrad/min)	PERCENT ERROR
Lung	8.767E-04	6.088E-02	6.176E-02	1.014E+00
Liver	1.312E-02	3.003E-01	3.134E-01	6.543E-01
Stomach	3.141E-02	4.827E-01	5.141E-01	8.692E-01
Small Intestine	1.300E+00	1.504E+00	2.803E+00	2.804E-01
Upper Large	1.746E+00	1.507E+00	3.253E+00	3.237E-01
Lower Large	3.174E-02	4.147E-01	4.464E-01	8.530E-01
Ovaries	4.949E-02	5.759E-01	6.253E-01	1.926E+00
Thyroid	0.000E+00	9.660E-03	9.660E-03	1.339E+01
Bone Surface	2.598E-02	7.381E-02	9.979E-02	4.630E-01
Trunk	2.052E-01	2.860E-01	4.913E-01	1.870E-01
Kidneys	5.083E-02	3.309E-01	3.818E-01	8.948E-01
Bladder	8.037E-03	2.719E-01	2.799E-01	1.210E+00
Spleen	1.060E-02	2.044E-01	2.150E-01	1.577E+00
Pancreas	1.718E-02	3.529E-01	3.701E-01	1.554E+00
Thymus	1.726E-06	2.236E-02	2.236E-02	8.589E+00
Adrenal	1.046E-02	2.128E-01	2.233E-01	2.704E+00
Heart	1.141E-03	8.071E-02	8.185E-02	1.728E+00
Brain	0.000E+00	3.977E-03	3.977E-03	5.750E+00
Breasts	2.857E-03	6.761E-02	7.047E-02	1.416E+00
Uterus	6.079E-02	7.165E-01	7.773E-01	1.016E+00
Red Marrow	9.470E-02	1.668E-01	2.615E-01	1.675E+00
Skin	2.131E-01	1.471E-01	3.601E-01	1.360E-01
Eye Lens	0.000E+00	3.803E-03	3.803E-03	2.619E+01

Table 3. Summary of Organ Dose Equivalents

NOTE: Average Quality factors are weighted by the dose equivalent. Also, photon dose equivalent = photon kerma (i.e., QF = 1).

ORGAN	NEUTRON DOSE EQ. (mrem/min)	AVERAGE ENERGY (Mev)	AVERAGE QF	TOTAL DOSE EQ. (mrem/min)	WT FACTOR
Lung	9.043E-03	1.537E+00	1.068E+01	6.992E-02	1.000E-01
Liver	1.404E-01	1.169E+00	1.107E+01	4.407E-01	0.000E+00
Stomach	3.369E-01	1.142E+00	1.113E+01	8.196E-01	5.200E-02
Small Intestine	1.331E+01	1.624E+00	1.072E+01	1.482E+01	5.200E-02
Upper Large	1.773E+01	1.708E+00	1.063E+01	1.924E+01	5.200E-02
Lower Large	3.419E-01	1.125E+00	1.116E+01	7.566E-01	5.200E-02
Ovaries	5.194E-01	1.335E+00	1.097E+01	1.095E+00	2.100E-01
Thyroid	0.000E+00	0.000E+00	0.000E+00	9.660E-03	4.000E-02
Bone Surface	2.322E-01	2.909E+00	9.433E+00	3.060E-01	3.000E-02
Trunk	2.228E+00	1.122E+00	1.129E+01	2.514E+00	5.200E-02
Kidneys	5.092E-01	1.737E+00	1.048E+01	8.402E-01	0.000E+00
Bladder	8.553E-02	1.178E+00	1.104E+01	3.574E-01	0.000E+00
Spleen	1.084E-01	1.442E+00	1.054E+01	3.128E-01	0.000E+00
Pancreas	1.855E-01	1.121E+00	1.111E+01	5.384E-01	0.000E+00
Thymus	1.834E-05	1.123E-05	1.091E+01	2.238E-02	0.000E+00
Adrenal	1.063E-01	1.623E+00	1.048E+01	3.191E-01	0.000E+00
Heart	1.181E-02	1.815E+00	1.090E+01	9.252E-02	0.000E+00
Brain	0.000E+00	0.000E+00	0.000E+00	3.977E-03	0.000E+00
Breasts	3.125E-02	1.065E+00	1.138E+01	9.886E-02	2.600E-01
Uterus	6.530E-01	1.161E+00	1.116E+01	1.369E+00	0.000E+00
Red Marrow	8.580E-01	2.759E+00	9.559E+00	1.025E+00	1.000E-01
Skin	2.363E+00	1.012E+00	1.150E+01	2.510E+00	0.000E+00
Eye Lens	0.000E+00	0.000E+00	0.000E+00	3.803E-03	0.000E+00
TOTAL					1.000E+00

EFFECTIVE DOSE EQUIVALENT (mrem/min): 2.36 (0.02)

Appendix D. Gamma Dose Rates for 500 keV

DATE: 14-MAY-1993 TIME: 14:47:36.00
PROGRAM TABULATE v. 1.6
RELEASE DATE: MAY 13, 1993

R.D. Stewart
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Richland, WA 99352
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MCNP VERSION 3B3
OUTPUT FILE CREATION DATE THU MAY 13 02:04:05

PHANTOM TYPE: Female
WEIGHT FACTORS: Female
BEAM AREA NORMALIZATION: 12.90
SOURCE WEIGHT (WGT): 19.6948
PHOTON ONLY PROBLEM (MODE P) w/ photon source.
PHOTON SOURCE ENERGY (MeV): .500

INCIDENT NEUTRON DIRECTION:
Azimuthal Angle (deg): 90.0
Polar Angle (deg): 180.0

RUN-TIME STATISTICS:
Particle Histories Executed: 3000000.
Total Execution Time (min) 412.40
Particles Per Minute: 7274.4907

TABLE 1. SUMMARY OF ORGAN FLUENCES AND AVG. ENERGIES.

ORGAN	NEUTRON FLUENCE (CM^{-2})	PERCENT ERROR	AVERAGE ENERGY (keV)	PHOTON FLUENCE (CM^{-2})	PERCENT ERROR	AVERAGE ENERGY (keV)
LUNG	0.000E+00	0.000E+00	0.000E+00	1.831E-02	4.700E-01	1.385E+02
LIVER	0.000E+00	0.000E+00	0.000E+00	9.595E-02	2.700E-01	1.433E+02
STOMACH	0.000E+00	0.000E+00	0.000E+00	1.407E-01	3.800E-01	1.465E+02
SMALL INTESTINE	0.000E+00	0.000E+00	0.000E+00	1.390E+00	5.000E-02	3.468E+02
UPPER LARGE	0.000E+00	0.000E+00	0.000E+00	1.655E+00	7.000E-02	3.784E+02
LOWER LARGE	0.000E+00	0.000E+00	0.000E+00	1.413E-01	3.500E-01	1.541E+02
OVARIES	0.000E+00	0.000E+00	0.000E+00	2.220E-01	7.800E-01	1.613E+02
THYROID	0.000E+00	0.000E+00	0.000E+00	1.206E-03	9.400E+00	1.058E+02
BONE SURFACE	0.000E+00	0.000E+00	0.000E+00	1.067E-01	7.000E-02	3.588E+02
TRUNK (MUSCLE)	0.000E+00	0.000E+00	0.000E+00	1.558E-01	4.000E-02	2.792E+02
KIDNEYS	0.000E+00	0.000E+00	0.000E+00	2.150E-01	2.800E-01	1.977E+02
BLADDER	0.000E+00	0.000E+00	0.000E+00	8.679E-02	5.400E-01	1.331E+02
SPLEEN	0.000E+00	0.000E+00	0.000E+00	8.769E-02	6.300E-01	1.528E+02
PANCREAS	0.000E+00	0.000E+00	0.000E+00	1.359E-01	6.300E-01	1.493E+02
THYMUS	0.000E+00	0.000E+00	0.000E+00	4.671E-03	4.670E+00	1.094E+02
ADRENALS	0.000E+00	0.000E+00	0.000E+00	1.048E-01	1.060E+00	1.719E+02
HEART	0.000E+00	0.000E+00	0.000E+00	2.441E-02	8.300E-01	1.223E+02
BRAIN	0.000E+00	0.000E+00	0.000E+00	1.639E-04	7.340E+00	1.244E+02
BREASTS	0.000E+00	0.000E+00	0.000E+00	1.361E-02	7.900E-01	1.345E+02
UTERUS	0.000E+00	0.000E+00	0.000E+00	2.445E-01	4.200E-01	1.586E+02
RED MARROW	0.000E+00	0.000E+00	0.000E+00	2.484E-01	2.507E-01	3.502E+02
SKIN	0.000E+00	0.000E+00	0.000E+00	8.822E-02	3.000E-02	3.432E+02
EYE LENS	0.000E+00	0.000E+00	0.000E+00	2.977E-04	2.712E+01	1.496E+02

TABLE 2. SUMMARY OF ORGAN KERMAS (absorbed doses).
NOTE: Associated errors are same as errors in fluence (i.e., application of pt. kernels is exact.)

ORGAN	NEUTRON KERMA (mrad/min)	PHOTON KERMA (mrad/min)	TOTAL KERMA (mrad/min)	PERCENT ERROR
LUNG	0.000E+00	1.236E-02	1.236E-02	4.700E-01
LIVER	0.000E+00	6.575E-02	6.575E-02	2.700E-01
STOMACH	0.000E+00	9.823E-02	9.823E-02	3.800E-01
SMALL INTESTINE	0.000E+00	2.478E+00	2.478E+00	5.000E-02
UPPER LARGE	0.000E+00	3.237E+00	3.237E+00	7.000E-02
LOWER LARGE	0.000E+00	1.046E-01	1.046E-01	3.500E-01
OVARIES	0.000E+00	1.732E-01	1.732E-01	7.800E-01
THYROID	0.000E+00	6.162E-04	6.162E-04	9.400E+00
BONE SURFACE	0.000E+00	1.999E-01	1.999E-01	7.000E-02
TRUNK (MUSCLE)	0.000E+00	2.205E-01	2.205E-01	4.000E-02
KIDNEYS	0.000E+00	2.093E-01	2.093E-01	2.800E-01
BLADDER	0.000E+00	5.504E-02	5.504E-02	5.400E-01
SPLEEN	0.000E+00	6.495E-02	6.495E-02	6.300E-01
PANCREAS	0.000E+00	9.783E-02	9.783E-02	6.300E-01
THYMUS	0.000E+00	2.451E-03	2.451E-03	4.670E+00
ADRENALS	0.000E+00	8.789E-02	8.789E-02	1.060E+00
HEART	0.000E+00	1.436E-02	1.436E-02	8.300E-01
BRAIN	0.000E+00	9.729E-05	9.729E-05	7.340E+00
BREASTS	0.000E+00	8.561E-03	8.561E-03	7.900E-01
UTERUS	0.000E+00	1.865E-01	1.865E-01	4.200E-01
RED MARROW	0.000E+00	4.459E-01	4.459E-01	2.507E-01
SKIN	0.000E+00	1.554E-01	1.554E-01	3.000E-02
EYE LENS	0.000E+00	2.078E-04	2.078E-04	2.712E+01

TABLE 3. SUMMARY OF ORGAN DOSE EQUIVALENTS x 1E-12.
NOTE: Average Quality factors are weighted by the dose equivalent.
Photon dose equivalent = photon kerma (i.e., QF = 1).
Avg. Energy is weighted by the dose equivalent.

ORGAN	NEUTRON DOSE EQ. (mrem/min)	AVERAGE ENERGY (Mev)	AVERAGE QF	TOTAL DOSE EQ. (mrem/min)	ICRP 26 WEIGHT FACTOR
LUNG	0.000E+00	0.000E+00	0.000E+00	1.236E-02	1.000E-01
LIVER	0.000E+00	0.000E+00	0.000E+00	6.575E-02	0.000E+00
STOMACH	0.000E+00	0.000E+00	0.000E+00	9.823E-02	5.200E-02
SMALL INTESTINE	0.000E+00	0.000E+00	0.000E+00	2.478E+00	5.200E-02
UPPER LARGE	0.000E+00	0.000E+00	0.000E+00	3.237E+00	5.200E-02
LOWER LARGE	0.000E+00	0.000E+00	0.000E+00	1.046E-01	5.200E-02
OVARIES	0.000E+00	0.000E+00	0.000E+00	1.732E-01	2.100E-01
THYROID	0.000E+00	0.000E+00	0.000E+00	6.162E-04	4.000E-02
BONE SURFACE	0.000E+00	0.000E+00	0.000E+00	1.999E-01	3.000E-02
TRUNK (MUSCLE)	0.000E+00	0.000E+00	0.000E+00	2.205E-01	5.200E-02
KIDNEYS	0.000E+00	0.000E+00	0.000E+00	2.093E-01	0.000E+00
BLADDER	0.000E+00	0.000E+00	0.000E+00	5.504E-02	0.000E+00
SPLEEN	0.000E+00	0.000E+00	0.000E+00	6.495E-02	0.000E+00
PANCREAS	0.000E+00	0.000E+00	0.000E+00	9.783E-02	0.000E+00
THYMUS	0.000E+00	0.000E+00	0.000E+00	2.451E-03	0.000E+00
ADRENALS	0.000E+00	0.000E+00	0.000E+00	8.789E-02	0.000E+00
HEART	0.000E+00	0.000E+00	0.000E+00	1.436E-02	0.000E+00
BRAIN	0.000E+00	0.000E+00	0.000E+00	9.729E-05	0.000E+00
BREASTS	0.000E+00	0.000E+00	0.000E+00	8.561E-03	2.600E-01
UTERUS	0.000E+00	0.000E+00	0.000E+00	1.865E-01	0.000E+00
RED MARROW	0.000E+00	0.000E+00	0.000E+00	4.459E-01	1.000E-01
SKIN	0.000E+00	0.000E+00	0.000E+00	1.554E-01	0.000E+00
EYE LENS	0.000E+00	0.000E+00	0.000E+00	2.078E-04	0.000E+00
TOTAL					1.000E+00

EFFECTIVE DOSE EQUIVALENT (mrem/min): 0.4096 (0.0007)

Appendix E. Gamma Dose Rates for 1 MeV

DATE: 14-MAY-1993 TIME: 14:46:53.00
PROGRAM TABULATE v. 1.6
RELEASE DATE: MAY 13, 1993

R.D. Stewart
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MCNP VERSION 3B3
OUTPUT FILE CREATION DATE WED MAY 12 14:06:13

PHANTOM TYPE: Female
WEIGHT FACTORS: Female
BEAM AREA NORMALIZATION: 12.90
SOURCE WEIGHT (WGT): 10.4862
PHOTON ONLY PROBLEM (MODE P) w/ photon source.
PHOTON SOURCE ENERGY (MeV): 1.000

INCIDENT NEUTRON DIRECTION:
Azimuthal Angle (deg): 90.0
Polar Angle (deg): 180.0

RUN-TIME STATISTICS:
Particle Histories Executed: 3000000.
Total Execution Time (min) 378.52
Particles Per Minute: 7925.6050

TABLE 1. SUMMARY OF ORGAN FLUENCES AND AVG. ENERGIES.

ORGAN	NEUTRON FLUENCE (CM^{-2})	PERCENT ERROR	AVERAGE ENERGY (keV)	PHOTON FLUENCE (CM^{-2})	PERCENT ERROR	AVERAGE ENERGY (keV)
LUNG	0.000E+00	0.000E+00	0.000E+00	8.573E-03	5.000E-01	1.826E+02
LIVER	0.000E+00	0.000E+00	0.000E+00	4.125E-02	2.900E-01	1.870E+02
STOMACH	0.000E+00	0.000E+00	0.000E+00	5.832E-02	4.300E-01	1.880E+02
SMALL INTESTINE	0.000E+00	0.000E+00	0.000E+00	7.364E-01	5.000E-02	7.441E+02
UPPER LARGE	0.000E+00	0.000E+00	0.000E+00	8.940E-01	6.000E-02	8.200E+02
LOWER LARGE	0.000E+00	0.000E+00	0.000E+00	6.101E-02	3.900E-01	2.055E+02
OVARIES	0.000E+00	0.000E+00	0.000E+00	9.755E-02	8.600E-01	2.193E+02
THYROID	0.000E+00	0.000E+00	0.000E+00	5.756E-04	1.035E+01	1.390E+02
BONE SURFACE	0.000E+00	0.000E+00	0.000E+00	6.818E-02	6.000E-02	7.843E+02
TRUNK (MUSCLE)	0.000E+00	0.000E+00	0.000E+00	7.590E-02	4.000E-02	5.621E+02
KIDNEYS	0.000E+00	0.000E+00	0.000E+00	1.023E-01	3.000E-01	3.112E+02
BLADDER	0.000E+00	0.000E+00	0.000E+00	3.710E-02	6.000E-01	1.679E+02
SPLEEN	0.000E+00	0.000E+00	0.000E+00	3.935E-02	6.800E-01	2.115E+02
PANCREAS	0.000E+00	0.000E+00	0.000E+00	5.947E-02	6.900E-01	1.986E+02
THYMUS	0.000E+00	0.000E+00	0.000E+00	2.190E-03	4.570E+00	1.436E+02
ADRENALS	0.000E+00	0.000E+00	0.000E+00	4.939E-02	1.120E+00	2.467E+02
HEART	0.000E+00	0.000E+00	0.000E+00	1.136E-02	8.900E-01	1.553E+02
BRAIN	0.000E+00	0.000E+00	0.000E+00	1.072E-04	6.450E+00	1.670E+02
BREASTS	0.000E+00	0.000E+00	0.000E+00	6.072E-03	8.600E-01	1.669E+02
UTERUS	0.000E+00	0.000E+00	0.000E+00	1.033E-01	4.700E-01	2.150E+02
RED MARROW	0.000E+00	0.000E+00	0.000E+00	1.563E-01	2.011E-01	7.633E+02
SKIN	0.000E+00	0.000E+00	0.000E+00	4.616E-02	3.000E-02	7.217E+02
EYE LENS	0.000E+00	0.000E+00	0.000E+00	2.187E-04	2.423E+01	1.664E+02

TABLE 2. SUMMARY OF ORGAN KERMAS (absorbed doses).
NOTE: Associated errors are same as errors in fluence (i.e., application of pt. kernels is exact.)

ORGAN	NEUTRON KERMA (mrad/min)	PHOTON KERMA (mrad/min)	TOTAL KERMA (mrad/min)	PERCENT ERROR
LUNG	0.000E+00	7.772E-03	7.772E-03	5.000E-01
LIVER	0.000E+00	3.794E-02	3.794E-02	2.900E-01
STOMACH	0.000E+00	5.380E-02	5.380E-02	4.300E-01
SMALL INTESTINE	0.000E+00	2.692E+00	2.692E+00	5.000E-02
UPPER LARGE	0.000E+00	3.593E+00	3.593E+00	6.000E-02
LOWER LARGE	0.000E+00	6.209E-02	6.209E-02	3.900E-01
OVARIES	0.000E+00	1.064E-01	1.064E-01	8.600E-01
THYROID	0.000E+00	3.946E-04	3.946E-04	1.035E+01
BONE SURFACE	0.000E+00	2.525E-01	2.525E-01	6.000E-02
TRUNK (MUSCLE)	0.000E+00	2.099E-01	2.099E-01	4.000E-02
KIDNEYS	0.000E+00	1.608E-01	1.608E-01	3.000E-01
BLADDER	0.000E+00	3.040E-02	3.040E-02	6.000E-01
SPLEEN	0.000E+00	4.147E-02	4.147E-02	6.800E-01
PANCREAS	0.000E+00	5.858E-02	5.858E-02	6.900E-01
THYMUS	0.000E+00	1.560E-03	1.560E-03	4.570E+00
ADRENALS	0.000E+00	6.128E-02	6.128E-02	1.120E+00
HEART	0.000E+00	8.658E-03	8.658E-03	8.900E-01
BRAIN	0.000E+00	8.655E-05	8.655E-05	6.450E+00
BREASTS	0.000E+00	4.892E-03	4.892E-03	8.600E-01
UTERUS	0.000E+00	1.103E-01	1.103E-01	4.700E-01
RED MARROW	0.000E+00	5.838E-01	5.838E-01	2.011E-01
SKIN	0.000E+00	1.632E-01	1.632E-01	3.000E-02
EYE LENS	0.000E+00	1.728E-04	1.728E-04	2.423E+01

TABLE 3. SUMMARY OF ORGAN DOSE EQUIVALENTS x 1E-12.
NOTE: Average Quality factors are weighted by the dose equivalent.
Photon dose equivalent = photon kerma (i.e., QF = 1).
Avg. Energy is weighted by the dose equivalent.

ORGAN	NEUTRON DOSE EQ. (mrem/min)	AVERAGE ENERGY (Mev)	AVERAGE QF	TOTAL DOSE EQ. (mrem/min)	ICRP 26 WEIGHT FACTOR
LUNG	0.000E+00	0.000E+00	0.000E+00	7.772E-03	1.000E-01
LIVER	0.000E+00	0.000E+00	0.000E+00	3.794E-02	0.000E+00
STOMACH	0.000E+00	0.000E+00	0.000E+00	5.380E-02	5.200E-02
SMALL INTESTINE	0.000E+00	0.000E+00	0.000E+00	2.692E+00	5.200E-02
UPPER LARGE	0.000E+00	0.000E+00	0.000E+00	3.593E+00	5.200E-02
LOWER LARGE	0.000E+00	0.000E+00	0.000E+00	6.209E-02	5.200E-02
OVARIES	0.000E+00	0.000E+00	0.000E+00	1.064E-01	2.100E-01
THYROID	0.000E+00	0.000E+00	0.000E+00	3.946E-04	4.000E-02
BONE SURFACE	0.000E+00	0.000E+00	0.000E+00	2.525E-01	3.000E-02
TRUNK (MUSCLE)	0.000E+00	0.000E+00	0.000E+00	2.099E-01	5.200E-02
KIDNEYS	0.000E+00	0.000E+00	0.000E+00	1.608E-01	0.000E+00
BLADDER	0.000E+00	0.000E+00	0.000E+00	3.040E-02	0.000E+00
SPLEEN	0.000E+00	0.000E+00	0.000E+00	4.147E-02	0.000E+00
PANCREAS	0.000E+00	0.000E+00	0.000E+00	5.858E-02	0.000E+00
THYMUS	0.000E+00	0.000E+00	0.000E+00	1.560E-03	0.000E+00
ADRENALS	0.000E+00	0.000E+00	0.000E+00	6.128E-02	0.000E+00
HEART	0.000E+00	0.000E+00	0.000E+00	8.658E-03	0.000E+00
BRAIN	0.000E+00	0.000E+00	0.000E+00	8.655E-05	0.000E+00
BREASTS	0.000E+00	0.000E+00	0.000E+00	4.892E-03	2.600E-01
UTERUS	0.000E+00	0.000E+00	0.000E+00	1.103E-01	0.000E+00
RED MARROW	0.000E+00	0.000E+00	0.000E+00	5.838E-01	1.000E-01
SKIN	0.000E+00	0.000E+00	0.000E+00	1.632E-01	0.000E+00
EYE LENS	0.000E+00	0.000E+00	0.000E+00	1.728E-04	0.000E+00
TOTAL					1.000E+00

EFFECTIVE DOSE EQUIVALENT (mrem/min): 0.4341 (0.0005)

Appendix F. Gamma Dose Rates for 2 MeV

DATE: 14-MAY-1993 TIME: 14:47:19.00
PROGRAM TABULATE v. 1.6
RELEASE DATE: MAY 13, 1993

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MCNP VERSION 3B3
OUTPUT FILE CREATION DATE WED MAY 12 20:25:05

PHANTOM TYPE: Female
WEIGHT FACTORS: Female
BEAM AREA NORMALIZATION: 12.90
SOURCE WEIGHT (WGT): 6.2379
PHOTON ONLY PROBLEM (MODE P) w/ photon source.
PHOTON SOURCE ENERGY (MeV): 2.000

INCIDENT NEUTRON DIRECTION:
Azimuthal Angle (deg): 90.0
Polar Angle (deg): 180.0

RUN-TIME STATISTICS:
Particle Histories Executed: 3000000.
Total Execution Time (min) 338.75
Particles Per Minute: 8856.0889

TABLE 1. SUMMARY OF ORGAN FLUENCES AND AVG. ENERGIES.

ORGAN	NEUTRON FLUENCE (CM^{-2})	PERCENT ERROR	AVERAGE ENERGY (keV)	PHOTON FLUENCE (CM^{-2})	PERCENT ERROR	AVERAGE ENERGY (keV)
LUNG	0.000E+00	0.000E+00	0.000E+00	4.030E-03	5.700E-01	2.228E+02
LIVER	0.000E+00	0.000E+00	0.000E+00	1.834E-02	3.400E-01	2.275E+02
STOMACH	0.000E+00	0.000E+00	0.000E+00	2.520E-02	5.100E-01	2.232E+02
SMALL INTESTINE	0.000E+00	0.000E+00	0.000E+00	4.313E-01	4.000E-02	1.557E+03
UPPER LARGE	0.000E+00	0.000E+00	0.000E+00	5.347E-01	6.000E-02	1.701E+03
LOWER LARGE	0.000E+00	0.000E+00	0.000E+00	2.682E-02	4.600E-01	2.529E+02
OVARIES	0.000E+00	0.000E+00	0.000E+00	4.174E-02	1.030E+00	2.777E+02
THYROID	0.000E+00	0.000E+00	0.000E+00	3.394E-04	9.580E+00	1.667E+02
BONE SURFACE	0.000E+00	0.000E+00	0.000E+00	4.696E-02	5.000E-02	1.647E+03
TRUNK (MUSCLE)	0.000E+00	0.000E+00	0.000E+00	4.018E-02	4.000E-02	1.160E+03
KIDNEYS	0.000E+00	0.000E+00	0.000E+00	4.907E-02	3.300E-01	4.575E+02
BLADDER	0.000E+00	0.000E+00	0.000E+00	1.643E-02	7.000E-01	1.985E+02
SPLEEN	0.000E+00	0.000E+00	0.000E+00	1.794E-02	7.900E-01	2.673E+02
PANCREAS	0.000E+00	0.000E+00	0.000E+00	2.654E-02	8.100E-01	2.449E+02
THYMUS	0.000E+00	0.000E+00	0.000E+00	1.028E-03	5.150E+00	1.770E+02
ADRENALS	0.000E+00	0.000E+00	0.000E+00	2.370E-02	1.270E+00	3.323E+02
HEART	0.000E+00	0.000E+00	0.000E+00	5.095E-03	1.030E+00	1.837E+02
BRAIN	0.000E+00	0.000E+00	0.000E+00	6.154E-05	6.700E+00	2.163E+02
BREASTS	0.000E+00	0.000E+00	0.000E+00	2.736E-03	1.000E+00	1.929E+02
UTERUS	0.000E+00	0.000E+00	0.000E+00	4.569E-02	5.500E-01	2.700E+02
RED MARROW	0.000E+00	0.000E+00	0.000E+00	1.060E-01	1.747E-01	1.606E+03
SKIN	0.000E+00	0.000E+00	0.000E+00	2.670E-02	3.000E-02	1.491E+03
EYE LENS	0.000E+00	0.000E+00	0.000E+00	4.699E-05	3.348E+01	1.943E+02

TABLE 2. SUMMARY OF ORGAN KERMAS (absorbed doses).
NOTE: Associated errors are same as errors in fluence (i.e., application of pt. kernels is exact.)

ORGAN	NEUTRON KERMA (mrad/min)	PHOTON KERMA (mrad/min)	TOTAL KERMA (mrad/min)	PERCENT ERROR
LUNG	0.000E+00	4.511E-03	4.511E-03	5.700E-01
LIVER	0.000E+00	2.082E-02	2.082E-02	3.400E-01
STOMACH	0.000E+00	2.799E-02	2.799E-02	5.100E-01
SMALL INTESTINE	0.000E+00	2.798E+00	2.798E+00	4.000E-02
UPPER LARGE	0.000E+00	3.762E+00	3.762E+00	6.000E-02
LOWER LARGE	0.000E+00	3.392E-02	3.392E-02	4.600E-01
OVARIES	0.000E+00	5.813E-02	5.813E-02	1.030E+00
THYROID	0.000E+00	2.745E-04	2.745E-04	9.580E+00
BONE SURFACE	0.000E+00	3.057E-01	3.057E-01	5.000E-02
TRUNK (MUSCLE)	0.000E+00	1.974E-01	1.974E-01	4.000E-02
KIDNEYS	0.000E+00	1.104E-01	1.104E-01	3.300E-01
BLADDER	0.000E+00	1.617E-02	1.617E-02	7.000E-01
SPLEEN	0.000E+00	2.411E-02	2.411E-02	7.900E-01
PANCREAS	0.000E+00	3.250E-02	3.250E-02	8.100E-01
THYMUS	0.000E+00	8.948E-04	8.948E-04	5.150E+00
ADRENALS	0.000E+00	3.956E-02	3.956E-02	1.270E+00
HEART	0.000E+00	4.643E-03	4.643E-03	1.030E+00
BRAIN	0.000E+00	6.590E-05	6.590E-05	6.700E+00
BREASTS	0.000E+00	2.594E-03	2.594E-03	1.000E+00
UTERUS	0.000E+00	6.168E-02	6.168E-02	5.500E-01
RED MARROW	0.000E+00	7.054E-01	7.054E-01	1.747E-01
SKIN	0.000E+00	1.657E-01	1.657E-01	3.000E-02
EYE LENS	0.000E+00	4.342E-05	4.342E-05	3.348E+01

TABLE 3. SUMMARY OF ORGAN DOSE EQUIVALENTS x 1E-12.
NOTE: Average Quality factors are weighted by the dose equivalent.
Photon dose equivalent = photon kerma (i.e., QF = 1).
Avg. Energy is weighted by the dose equivalent.

ORGAN	NEUTRON DOSE EQ. (mrem/min)	AVERAGE ENERGY (Mev)	AVERAGE QF	TOTAL DOSE EQ. (mrem/min)	ICRP 26 WEIGHT FACTOR
LUNG	0.000E+00	0.000E+00	0.000E+00	4.511E-03	1.000E-01
LIVER	0.000E+00	0.000E+00	0.000E+00	2.082E-02	0.000E+00
STOMACH	0.000E+00	0.000E+00	0.000E+00	2.799E-02	5.200E-02
SMALL INTESTINE	0.000E+00	0.000E+00	0.000E+00	2.798E+00	5.200E-02
UPPER LARGE	0.000E+00	0.000E+00	0.000E+00	3.762E+00	5.200E-02
LOWER LARGE	0.000E+00	0.000E+00	0.000E+00	3.392E-02	5.200E-02
OVARIES	0.000E+00	0.000E+00	0.000E+00	5.813E-02	2.100E-01
THYROID	0.000E+00	0.000E+00	0.000E+00	2.745E-04	4.000E-02
BONE SURFACE	0.000E+00	0.000E+00	0.000E+00	3.057E-01	3.000E-02
TRUNK (MUSCLE)	0.000E+00	0.000E+00	0.000E+00	1.974E-01	5.200E-02
KIDNEYS	0.000E+00	0.000E+00	0.000E+00	1.104E-01	0.000E+00
BLADDER	0.000E+00	0.000E+00	0.000E+00	1.617E-02	0.000E+00
SPLEEN	0.000E+00	0.000E+00	0.000E+00	2.411E-02	0.000E+00
PANCREAS	0.000E+00	0.000E+00	0.000E+00	3.250E-02	0.000E+00
THYMUS	0.000E+00	0.000E+00	0.000E+00	8.948E-04	0.000E+00
ADRENALS	0.000E+00	0.000E+00	0.000E+00	3.956E-02	0.000E+00
HEART	0.000E+00	0.000E+00	0.000E+00	4.643E-03	0.000E+00
BRAIN	0.000E+00	0.000E+00	0.000E+00	6.590E-05	0.000E+00
BREASTS	0.000E+00	0.000E+00	0.000E+00	2.594E-03	2.600E-01
UTERUS	0.000E+00	0.000E+00	0.000E+00	6.168E-02	0.000E+00
RED MARROW	0.000E+00	0.000E+00	0.000E+00	7.054E-01	1.000E-01
SKIN	0.000E+00	0.000E+00	0.000E+00	1.657E-01	0.000E+00
EYE LENS	0.000E+00	0.000E+00	0.000E+00	4.342E-05	0.000E+00
TOTAL					1.000E+00

EFFECTIVE DOSE EQUIVALENT (mrem/min): 0.4476 (0.0005)

ARGONNE
NATIONAL
LABORATORY

INTRA-LABORATORY MEMO

DATE: April 15, 1993

TO: Dr. McLouis J. Robinet

FROM: Dr. David J. Grdina

SUBJECT: **HPRT and Chromosome Analysis of ANL Individual Exposed to Neutrons at the IPNS Facility.**

We have completed the analysis of the exposed individual's blood sample which you supplied to us. Both the mutation frequency and the percent of chromosome aberrations are within the normal range. All materials from this analysis will be sent to you for your files. We will do all that we can to facilitate your monitoring of this situation.

Encs.

cc: E. Huberman
J. Schwartz
D. Haugen

RECEIVED
Health Physics Section
APR 19 1993

ARGONNE
NATIONAL
LABORATORY

INTRA-LABORATORY MEMO

To: D. Grdina
From: J. Schwartz
Date: April 12, 1993
Subject: Final report on blood sample drawn on March 29, 1993

Short term cultures were set up on Monday afternoon. Cultures were harvested on Wednesday afternoon.

Standard Giemsa Analysis

One hundred and fifty first-division metaphases were scored. Three cells (2.0 %) were found to have structural aberrations. Two cells had chromatid-type aberrations; 1 isochromatid deletion and 1 chromatid deletion. These types of aberrations are not thought to be induced by ionizing radiation exposure of peripheral blood G_0 lymphocytes. One cell had a chromosome-type aberration, an interstitial deletion. The frequency of chromosome-type aberrations, 0.7%, is within normal reported ranges.

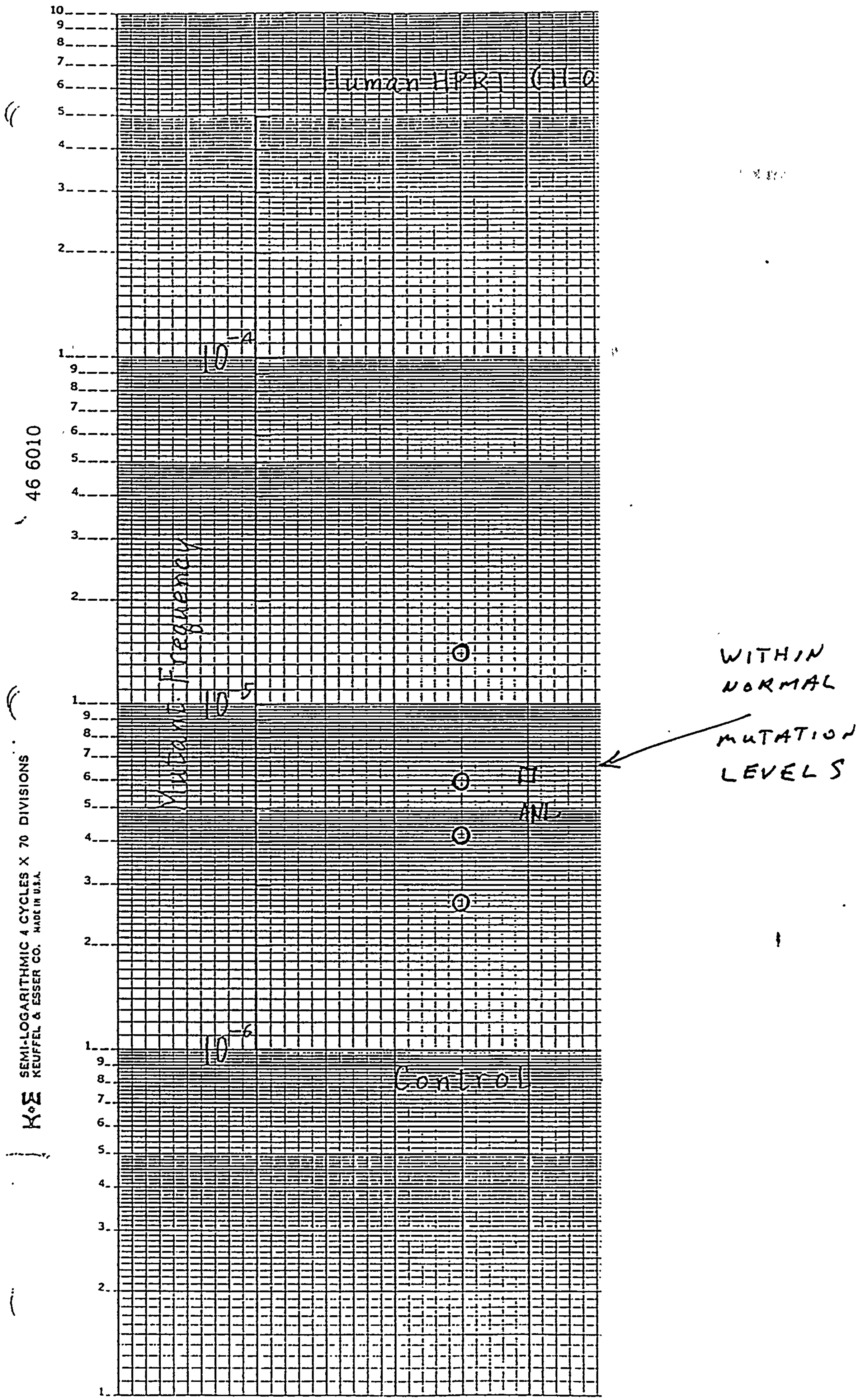
Flourescence *in situ* Hybridization Analysis

Slides were stained to detect alterations in either chromosome 7 or the X chromosome. A total of 1,794 metaphases on 4 slides were analyzed. One acentric fragment and 2 balanced translocations were found. When corrected for DNA content, this is equivalent to a total aberration frequency of 1.6%. This is within normal reported ranges.

Conclusion

The frequencies and types of chromosome aberrations, analyzed by standard Giemsa and fluorescent *in situ* hybridization staining procedures, are within normal reported ranges for unexposed individuals.

All slides and materials will be given to Dr. McLouis Robinet.


Human HPRT
Mutant Frequency
10^-4
10^-5
10^-6
Control
WITHIN NORMAL MUTATION LEVELS
46 6010
K&E SEMI-LOGARITHMIC 4 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

ANL – 1

4/14/93 Wed.

CM (0.2)	CE	6TG (1×10^{4})	CE	Mf
5/192	0.1319	4/480	8.3682×10^{-7}	6.3428×10^{-6}

ARGONNE
NATIONAL
LABORATORY

INTRA-LABORATORY MEMO

To: McLouis Robinet
From: Jeff Schwartz
Date: November 12, 1993
Subject: Dose Estimates from Blood Sample of 3/29/93

It is not possible to base any estimate of dose on the single sample we analyzed. The chromosome mutation frequency was within normal reported ranges for unexposed individuals and we had no information on the baseline pre-exposure levels of chromosome mutations. The assay we used has been reported to detect effects of exposures as low as 10-25 cGy of ^{60}Co gamma rays. I hope this information is useful. Please let me know if I can provide any other assistance.

RECEIVED
Health Physics Section
NOV 15 1993
Ct:
Filed:

APPENDIX E

Memo from M. J. Robinet to R. A. Wynveen dated April 20, 1993

ARGONNE NATIONAL LABORATORY

INTRA-LABORATORY MEMO

April 20, 1993

To:	R. A. Wynveen	Director, ESH
From:	M. J. Robinet	Section Head, ESH-HP
Subject:	*Status of Dose Estimate for Person Exposed in IPNS FI Beam - March 17, 1993*	

Dose Results to Date

All of the measurements scheduled for April 7 and 8 in the IPNS FI beam were completed as planned. However, the CR-39 dosimeters (which will give information on the dose from neutrons above 0.1 MeV) are still being processed.

Based on the measurements and results to date, we have the following preliminary information:

1. Approximate neutron entrance dose rate

   - 0.1 rad/min — measured with tissue equivalent ion chamber in water phantom
   - 0.2 rad/min — calculated from Monte Carlo spectra provided by IPNS
   - 0.5 rad/min — measured by TLD on tissue equivalent phantom

2. Based on the neutron spectra provided by IPNS, approximately 73% of the entrance neutron dose equivalent is calculated to be due to neutrons with energies between 0.2 and 2 MeV. In this energy range, the quality factor is at least 10.

3. At a depth of 4 cm in tissue equivalent material, the gamma dose rate (50 mrad/min) is approximately the same as the neutron dose rate. The gamma fraction of the dose is much greater than was expected.

4. Dose rate to ovaries (based on TLDs in phantom)

   - 5.8 mrad/min (thermal neutrons)
   - 6.8 mrad/min (gamma)

5. Maximum dose rate to any portion of stomach (based on TLD in phantom)

   - 100 mrad/min (thermal neutrons)
   - 122 mrad/min (gamma)

Whole Body Effective Dose

Because we do not yet have results from the CR-39 dosimeters placed in the polyethylene block phantom, we still do not really know the dose contribution to specific organs from high energy neutrons. A refinement of the estimate for the whole body effective dose can be done only after we have the CR-39 data.

Results of Chromosome and HPRT Analysis

Chromosome and HPRT analysis done by ANL show that both the percent of chromosome aberration and the mutation frequency are within the normal range.

Pending

- The FERMILAB quality factor measurements are still being analyzed.
- CR-39 dosimeter data is expected within a week.
- Chromosome aberration data from Oak Ridge is expected within a week.
- Bubble dosimeter data is expected within a week.
- Arrangements are being made for Battelle to make a Monte Carlo calculation of the whole body effective dose.
- FERMILAB delivery of known depth doses (in rads) to the phantom is scheduled for April 28, 1993. This will provide a true calibration of the TLD at each position within the phantom.

MJR/cs

cc: File

APPENDIX F

Memo from R. E. Toohey to R. A. Wynveen dated April 26, 1993

ARGONNE
NATIONAL
LABORATORY

Intra-Laboratory Memo

April 26, 1993

TO: R. A. Wynveen, Director, ESH 210

FROM: R. E. Toohey Section Head, ESH-DA 200

SUBJ: Dose reconstruction for IPNS exposure

I am hereby providing you with what I consider to be a defensible effective dose equivalent number for the above incident. Note that the modifier I use is "defensible", not "preliminary", "provisional", or "final". I obtained this number primarily from the data collected with the RANDO female phantom. In each slab or slice of the phantom, I averaged the gamma-ray (TLD700) and slow neutron (TLD600) doses for each organ in the slab. I then summed the individual slab doses to obtain total organ doses. I then took the ratio of CR39 dose to TLD600 dose measured in a polystyrene block phantom to compute fast neutron organ doses. I used neutron quality factors from 5480.11 weighted by the IPNS spectral data (Q=3.35 for slow neutrons and 10.35 for fast) to obtain organ dose equivalents. I then used the ICRP30 weighting scheme to obtain a (whole-body) effective dose equivalent value. Because of the various estimates of time she actually spent in the beam, I am reporting an EDE rate.

The EDE rate is 380 mrem per minute.

The components of this value are: gamma-ray, 36 mrem/min; slow neutron, 94 mrem/min, and fast neutron, 250 mrem/min. Some of the uncertainties in this figure include: use of a single average value for fast to slow neutron dose ratio, differences between the subject and the RANDO phantom, ICRP30 methodology vs. ICRP60, approximate weighted Q-values, and assuming the bone surface dose is the same as the red marrow dose. However, I feel that the uncertainties about the amount of time she actually spent in the beam and the various orientations of her body are much greater than the uncertainties is the dose calculations. I will be happy to discuss this calculation in detail at your pleasure.

cc: M. M. Torres
M. J. Robinet
file

p.s. As a reminder, dosimetry values are to be released outside ESH only by R. A. Wynveen

ARGONNE
NATIONAL
LABORATORY

INTRA-LABORATORY MEMO

January 31, 1995

TO: File

FROM: R.A. Wynveen ESH Division Director

SUBJECT: Dose Reconstruction for IPNS Exposure

Further to R.E. Toohey's April 26, 1993 memo to me, this is to provide notification to those interested parties that the p.s. statement no longer is in effect and is hereby released.

Should there be any further questions, please do not hesitate to contact my office.

RAW/mks

APPENDIX G

Memo from R. E. Toohey to R. A. Wynveen dated April 28, 1993

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ARGONNE NATIONAL LABORATORY

RECEIVED ... 29 1993

Intra-Laboratory Memo

April 28, 1993

TO: R. A. Wynveen, Director, ESH

FROM: R. E. Toohey *R E Toohey* Section Head, ESH-DA 200

SUBJ: Neutron Dosimetry for PNS Incident

This memo is intended to describe in detail how I arrived at a value for the total effective dose equivalent (TEDE) rate to be used in assessing the PNS incident. The calculations were made in two different ways: one based on ICRP-30 dosimetry and neutron quality factors, and one based on ICRP-60 dosimetry and neutron radiation weighting factors. Because current DOE regulations are based on the former, the assigned dose of record for this incident should be also.

The assumptions made in these calculations are listed below, in no particular order:

1. Internal dose (from activation products) is negligible; the only components to be considered are external gamma-rays, low-energy (<100 keV), and high-energy (>100 keV) neutrons.
2. The TLD-600 dosimeter response to high-energy neutrons is negligible; and the response to low-energy neutrons in the Phoenix beam is the same as to a D2O-moderated Cf-252 spectrum.
3. The CR-39 track-etch dosimeters respond only to high-energy neutrons; and the response to high-energy neutrons in the Phoenix beam is the same as to an unmoderated Pu-Be spectrum.
4. The female Rando phantom is an adequate representation of the subject.
5. The ratio of high-energy to low-energy neutron dose in the phantom and in the individual is the same as that measured in a polystyrene block phantom, and is approximately independent of depth.
6. The dose to bone surface equals the dose to red marrow, the dose to the thyroid equals the dose to the thymus, and the dose to the lower large intestine equals the dose to the upper large intestine; these are minor components of the effective dose equivalent.
7. The differences in the orientation of the subject's body for the entire time that any part of her body was in the beam are not taken into account.
8. The neutron spectrum at the Phoenix beam line is that listed in the memo from Crawford to Ruzicka dated 4/7/93.

The female Rando phantom is a model of the female torso constructed of tissue-equivalent materials, and arrayed in a set of horizontal slabs. Different organs are contained in the phantom, most of which extend through several slabs. Thermoluminescent dosimeters (TLD chips of LiF) were placed at various locations in the various organs of the phantom, combining TLD600 and TLD700 chips. The

TLD700 chips measure the gamma-ray dose directly; the TLD600 chips respond to both gamma and low-energy neutrons, and the neutron dose is obtained by subtracting out the gamma dose measured with the TLD700. The phantom was oriented with the Phoenix beam centered on its umbilicus and irradiated for 20 minutes. The dosimeters were processed in our lab in building 202. Thus the gamma-ray and low-energy neutron dose components were measured directly. The doses to the dosimeters contained in a given organ were averaged over each single slab of the phantom. Then the organ dose was obtained by summing the averaged slab doses over the several slabs containing the organ. The high-energy neutron dose component was scaled from the low-energy dose by using an average dose ratio of CR-39 to TLD600 dosimeters irradiated in the Phoenix beam line at about every cm of depth in a polystyrene block phantom. The average ratio used was 0.86 (except for skin). This may be an underestimate; inspection of the data shows that apparently low values were recorded around 10 cm; a more accurate value for the ratio may be 1.0. However, this difference is small considering the many uncertainties in the dose reconstruction, both as tabulated in the assumptions above, and in the various estimates of the actual amount of time the subject spent in the beam.

Values for the neutron quality factor for the ICRP30 calculation were obtained by weighting the values given in Figure 3 of DOE Order 5480.11 with the Phoenix spectrum; similarly, values of the neutron radiation weighting factor for the ICRP60 calculations were obtained by weighting the values in Table 1 of ICRP60 with the Phoenix spectrum. In like manner, tissue weighting factors for ICRP30 were taken from Appendix 2B of the DOE RadCon Manual, and for ICRP60 were taken from Table 2 of ICRP60. Finally, effective dose equivalent rates were obtained by summing the weighted organ dose equivalent rates.

The result of the ICRP30 calculation is: 340 mrem/min.

The result of the ICRP60 calculation is: 840 mrem/min.

My (hand-written) tables showing the calculations are attached, along with figures showing depth-dose curves for the dosimeters in the polystyrene block phantom at the Phoenix beam line and the CR-39 to TLD600 dose ratio.

ICRP 30 CALCULATION

1. Neutron Quality Factor:

a) < 100 keV (TLD 600 Data)

1)	Values up to 1 keV,	Q = 2
2)	at 10 keV,	Q = 2.5
3)	at 100 keV,	Q = 7.5

F (0;1 keV) =	2.78×10^6	Q = 2
1 - 2.15 keV	2.76×10^5	Q = 2.1
2.15 - 4.64 keV	2.82×10^5	Q = 2.2
4.64 - 10 keV	2.88×10^5	Q = 2.4
10 - 21.5 keV	3.00×10^5	Q = 3
21.5 - 46.4 keV	3.19×10^5	Q = 5
46.4 - 100 keV	3.80×10^5	Q = 7

Wtd Q = 2.73

b) > 100 keV (CR 39 data)

100 - 215 keV	4.66×10^5	Q = 7.5
215 - 464 keV	4.90×10^5	Q = 9
464 - 1000 keV	3.68×10^5	Q = 11
1000 - 2150 keV	2.33×10^5	Q = 10
2150 - 4640 keV	0.92×10^5	Q = 9
4640 - 1000 keV	0.25×10^5	Q = 7

Wtd Q = 9.14

ICRP 30 CALCULATION

	mrad/min			mrem/min					
PHANTOM ORGAN	γ	$M_<$	$N_>$	γ $Q=1$	$Q_n=2.73$	$Q_n=9.14$	TODE	W_T	TEDE
Brain	0.5	0.06	0.05	0.5	0.2	0.5	1.2		
Esophagus	0.5	0.12	0.10	0.5	0.3	0.9	1.7		
Thyroid	0.5	0.13	0.11	0.5	0.4	1.0	1.9	.03	0.06
Lung	2.0	0.83	0.71	2.0	2.3	6.5	10.8	.12	1.3
RM	12.4	9.8	8.4	12.4	26.8	76.8	116	.12	13.9
Liver	6.0	5.8	5.0	6.0	15.8	45.7	67.5		
Spleen	2.9	2.9	2.5	2.9	7.9	22.9	33.7		
Pancreas	11.2	9.3	8.0	11.2	25.4	73.1	110	.06	6.6
Adrenals	4.6	3.2	2.8	4.6	8.7	25.6	38.9		
Kidney	6.0	9.3	8.0	6.0	25.4	73.1	104		
Stomach	221	180	155	221	491	1417	2129	.06	128
SI	172	134	115	172	366	1051	1589	.06	95.3
LLI	50.8	36	31	50.8	98.3	283	432	.06	25.9
ULI	50.8	36	31	50.8	98.3	283	432	.06	25.9
BS	12.4	9.8	8.4	12.4	26.8	76.8	116	.03	3.5
Ovaries	13.7	12	10.3	13.7	32.8	94.1	141	.25	35.3
Uterus	2.3	4.3	3.7	2.3	11.7	33.8	47.8		
Bladder	1.0	3.4	2.9	1.0	9.3	26.5	36.8		
Eyes	0.4	0.1	0.1	0.4	0.3	0.9	1.6		
Breast	1.4	0.3	0.3	1.4	0.8	2.7	4.9	.15	0.7
Skin (in beam)	117	116	138	117	317	1261	1695		
									336.4

ICRP 60 CALCULATION

Neutron Radiation Weighting Factor

ICRP 60:

< 10 keV	5
10 - 100 keV	10
100 - 2 MeV	20
2 - 20 MeV	10
> 20 Mev	5

a) E (n) < 100 keV (TLD 600 data) W

F(O, 10 keV) = 3.62×10^6	5
10 - 100 keV = (4.62 - 3.62) = 1.0×10^6	10

$\overline{W} = 6.08$

b) E(n) > 100 keV (CR 39 data) W

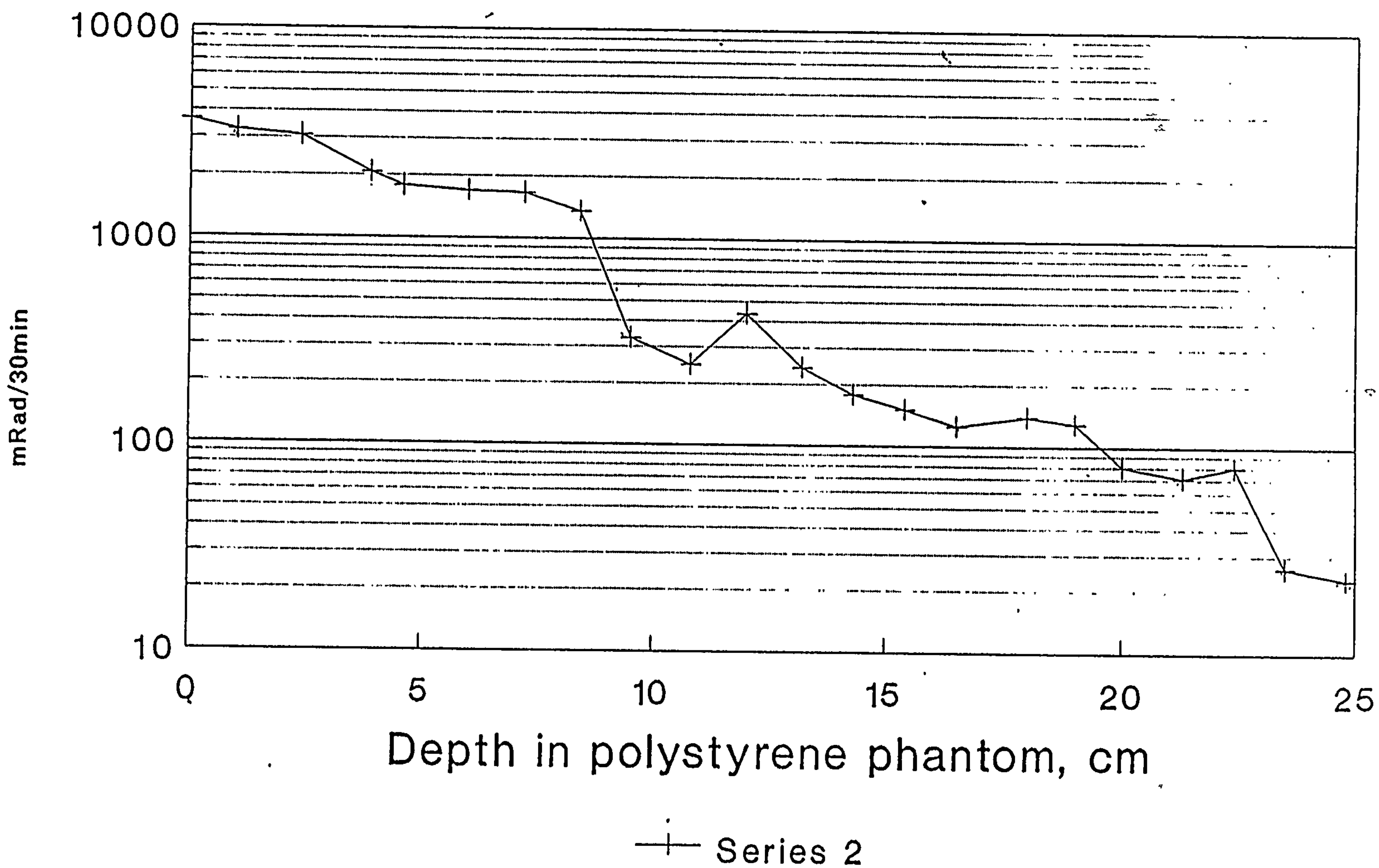
100 keV - 2150 keV = (6.18 - 4.62)	20
2150 - 10 Mev = (6.30 - 6.18)	10

$\overline{W} = 19.3$

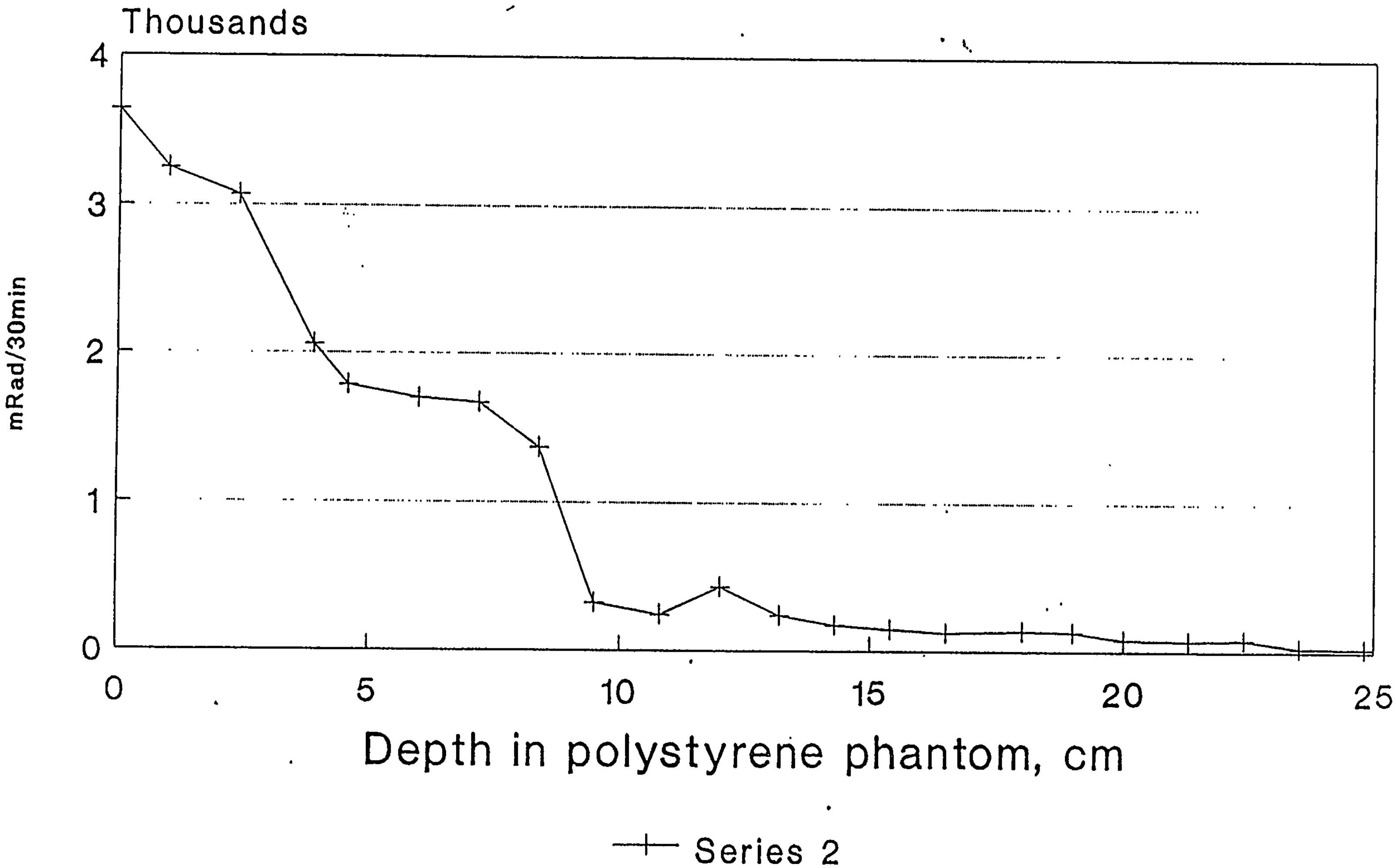
ICRP 60 CALCULATION

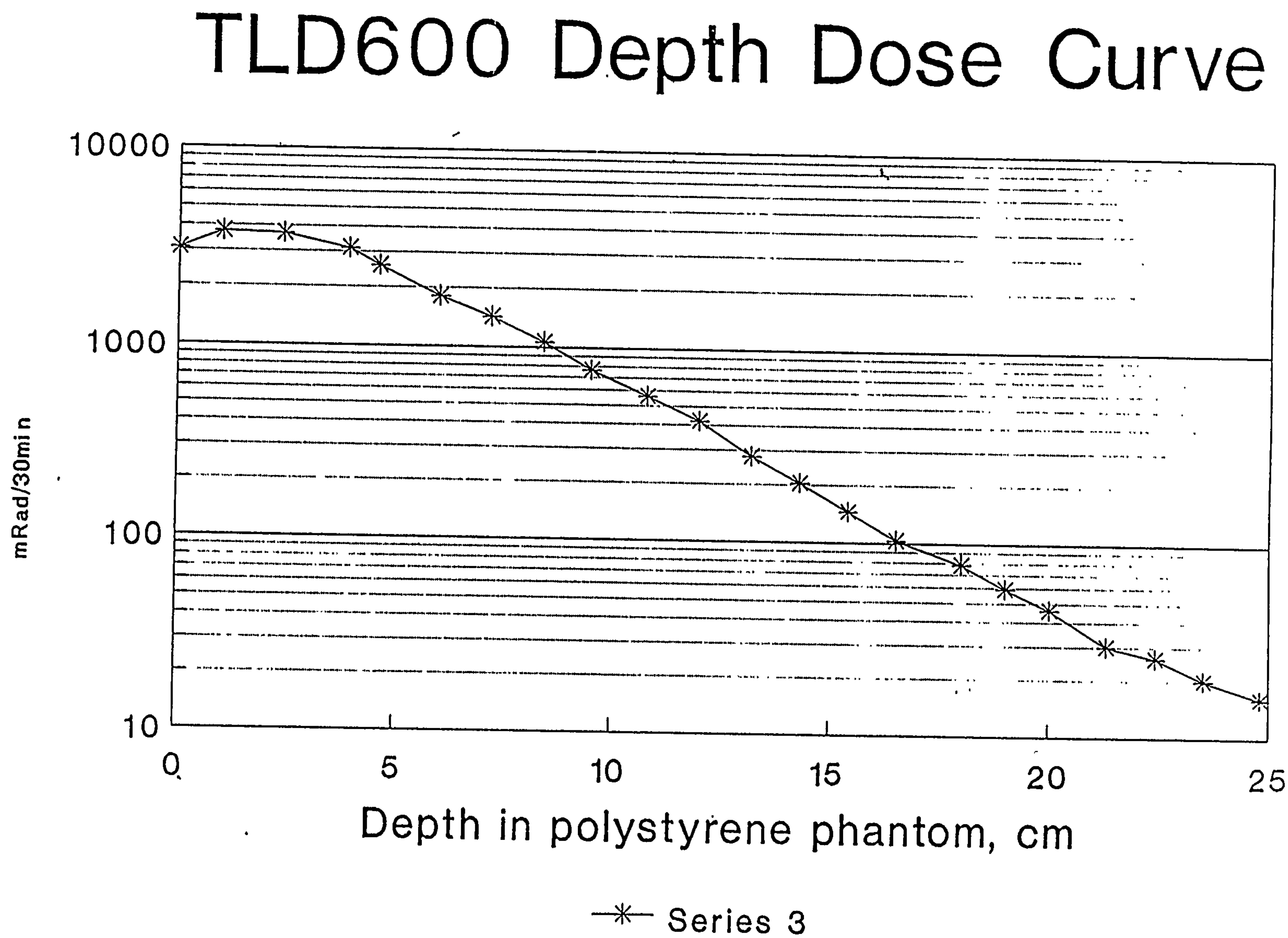
ORGAN	mrad/min γ	mrad/min $N_<$	mrad/min $N_>$	mrem/min γ Q=1	mrem/min $Q_n=6.08$	mrem/min $Q_n=19.3$	TODE	W_T	TEDE
Brain	0.5	0.06	0.05	0.5	0.4	1.0	1.9		
Esophagus	0.5	0.12	0.10	0.5	0.7	1.9	3.1	.05	0.2
Thyroid	0.5	0.13	0.11	0.5	0.8	2.1	3.4	.05	0.2
Lung	2.0	0.83	0.71	2.0	5.0	13.7	20.7	.12	2.5
RM	12.4	9.8	8.4	12.4	59.6	162	234	.12	28.1
Liver	6.0	5.8	5.0	6.0	35.3	96.5	138	.05	6.9
Spleen	2.9	2.9	2.5	2.9	17.6	48.3	68.8		
Pancreas	11.2	9.3	8.0	11.2	56.5	154	222		
Adrenals	4.6	3.2	2.8	4.6	19.5	54.0	78.1		
Kidney	6.0	9.3	8.0	6.0	56.5	154	216		
Stomach	221	180	155	221	1094	2992	4307	.12	517
SI	172	134	115	172	815	2220	3207	.025	80.2
Colon	50.8	36	31	50.8	219	598	868	.12	104
ULI	50.8	36	31	50.8	219	598	868		
BS	12.4	9.8	8.4	12.4	59.6	162	234	.01	2.3
Ovaries	13.7	12	10.3	13.7	73.0	199	286	0.2	57.2
Uterus	2.3	4.3	3.7	2.3	26.1	71.4	99.8		
Bladder	1.0	3.4	2.9	1.0	20.7	56.0	77.7	0.05	3.9
Eyes	0.4	0.1	0.1	0.4	0.6	1.9	2.9		
Breast	1.4	0.3	0.3	1.4	1.8	5.8	9.0	.05	0.5
Skin (in beam)	117	116	138	117	705	2663	3485	.01	0.3
(Assume 1% of skin)						Remainder	1558	.025	39.0
									842.3

CR-39 Depth Dose Curve

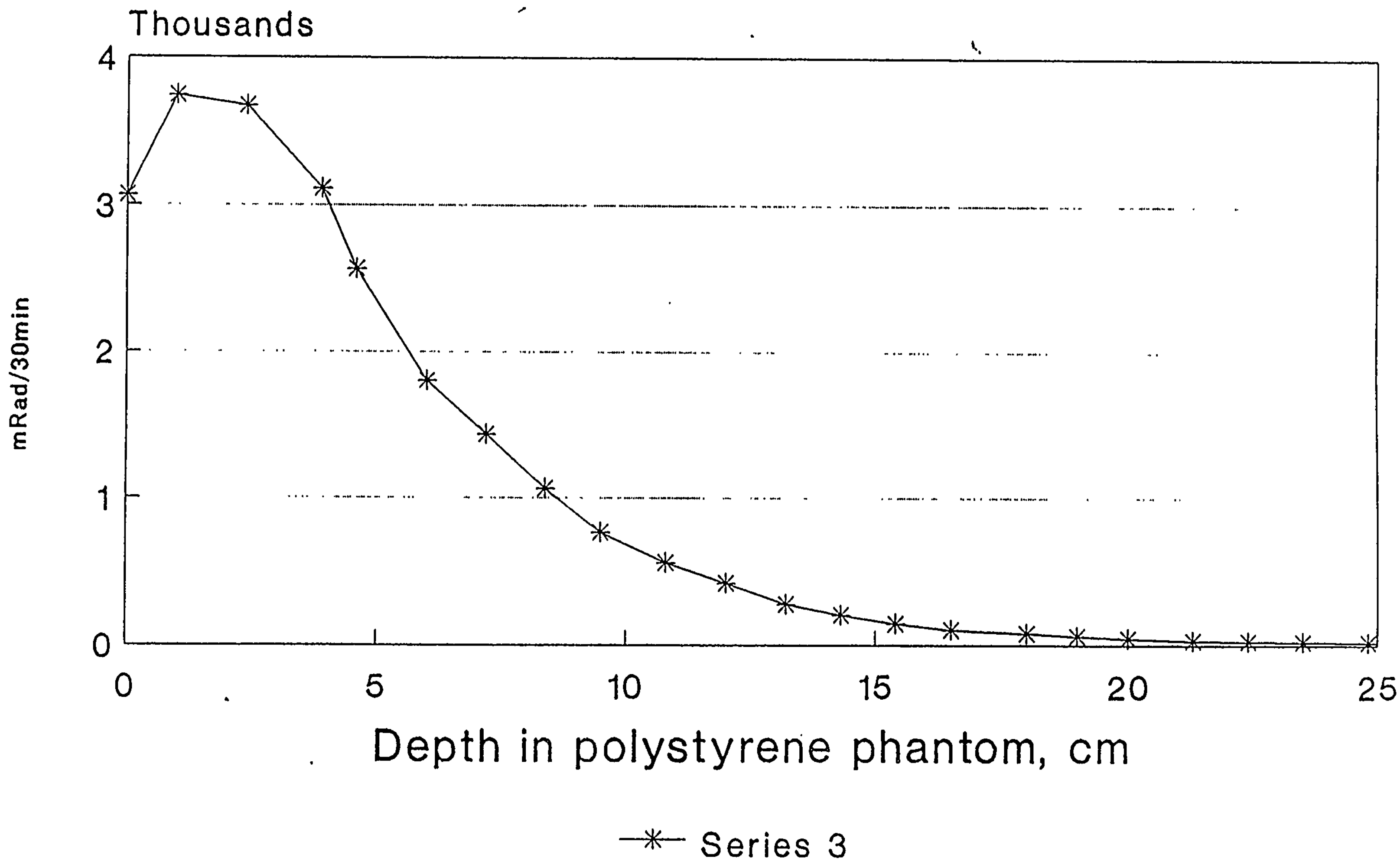


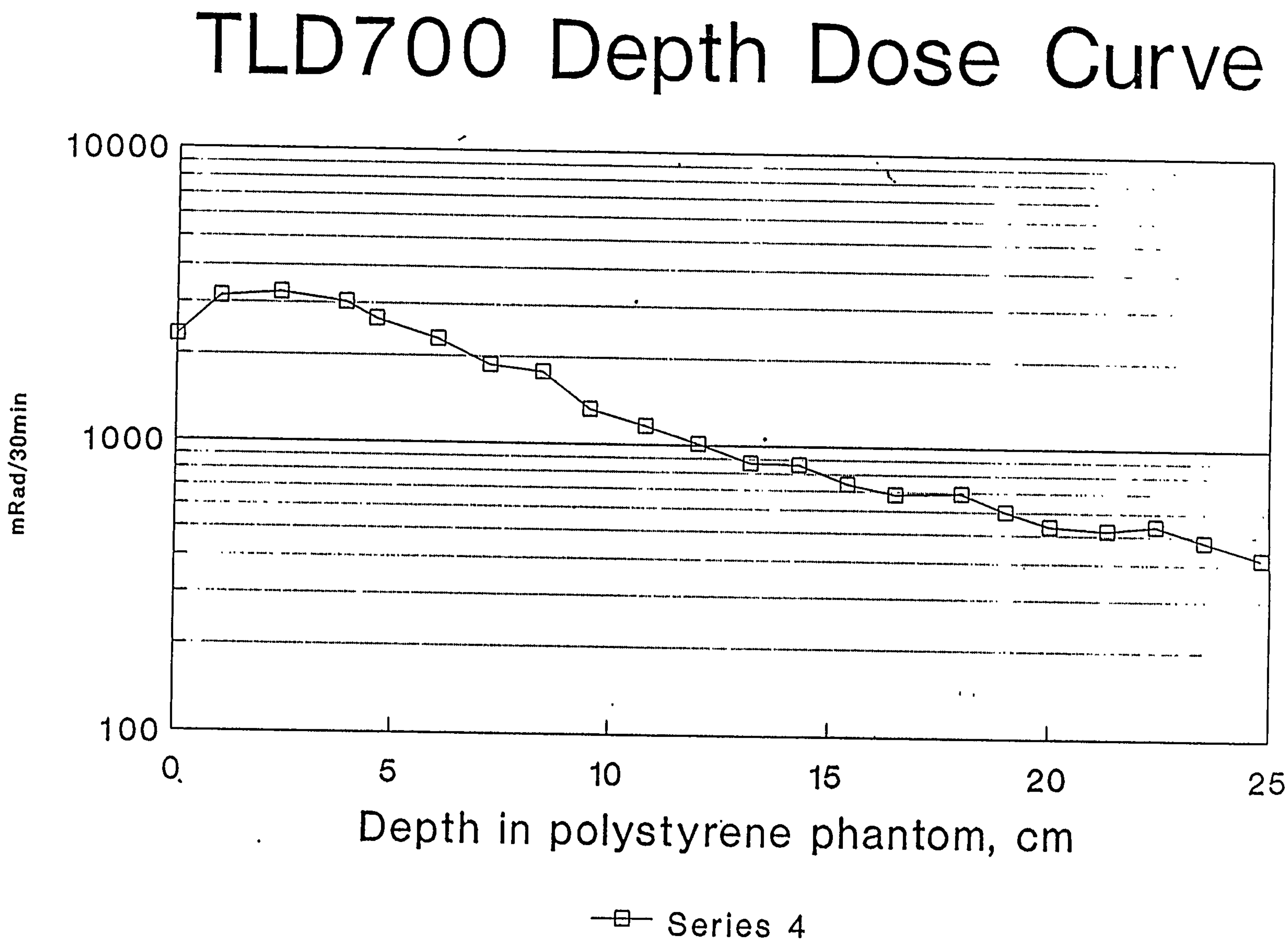
CR-39 Depth Dose Curve



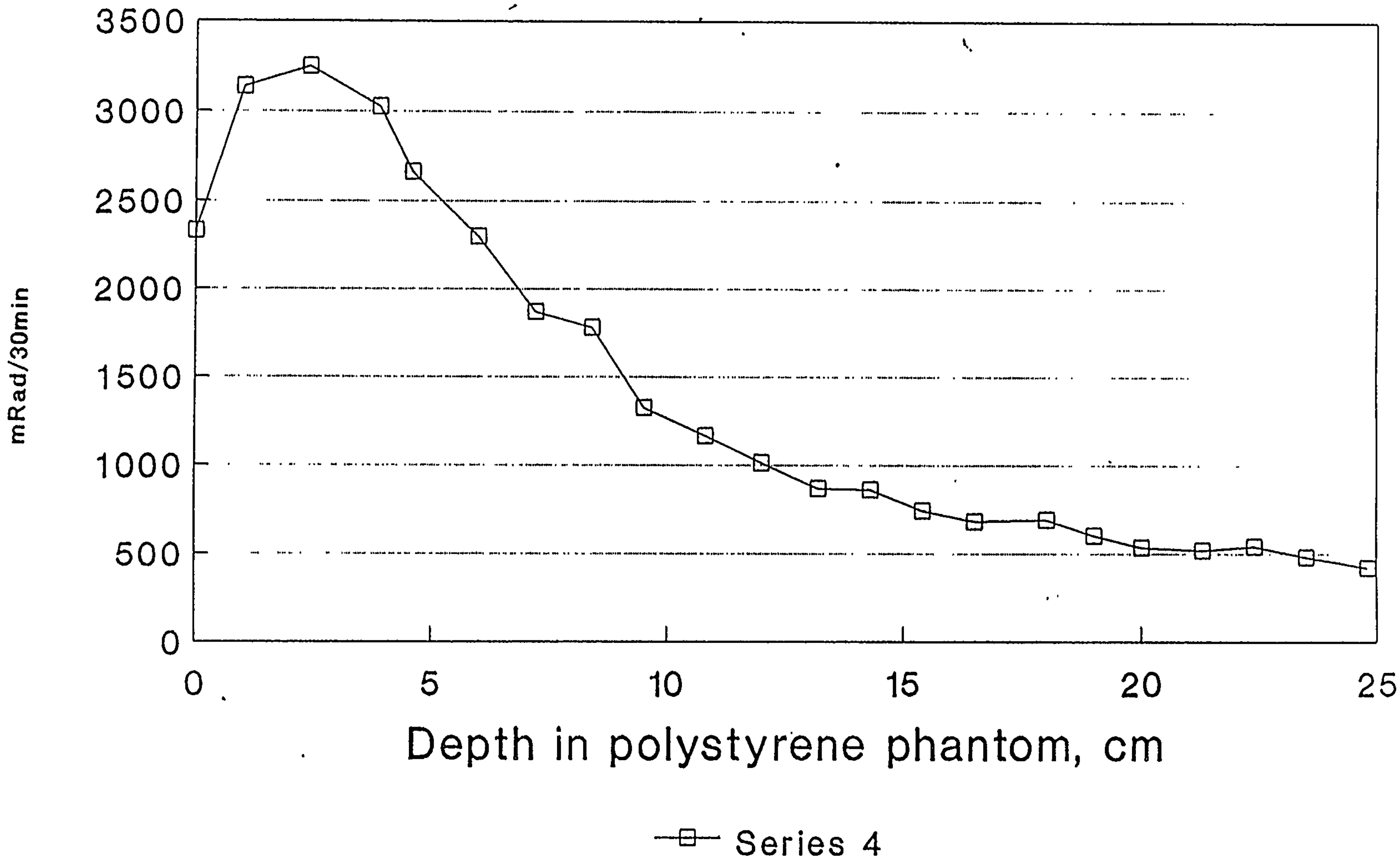

TLD600 Depth Dose Curve
10000
1000
100
10
mRad/30min
0
5
10
15
20
25
Depth in polystyrene phantom, cm
Series 3

TLD600 Depth Dose Curve

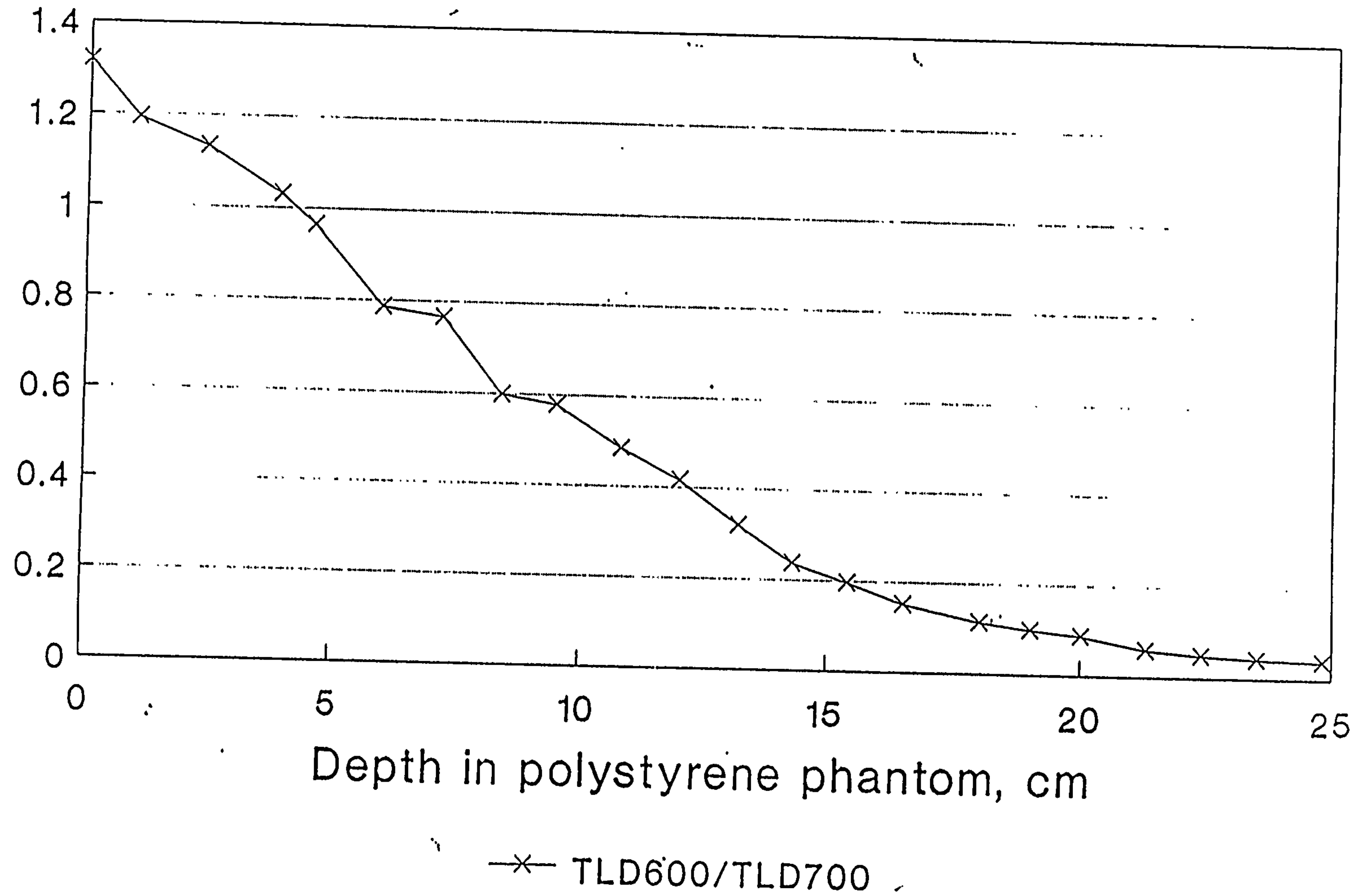



TLD700 Depth Dose Curve
10000
1000
100
mRad/30min
0.
5
10
15
20
25
Depth in polystyrene phantom, cm
Series 4

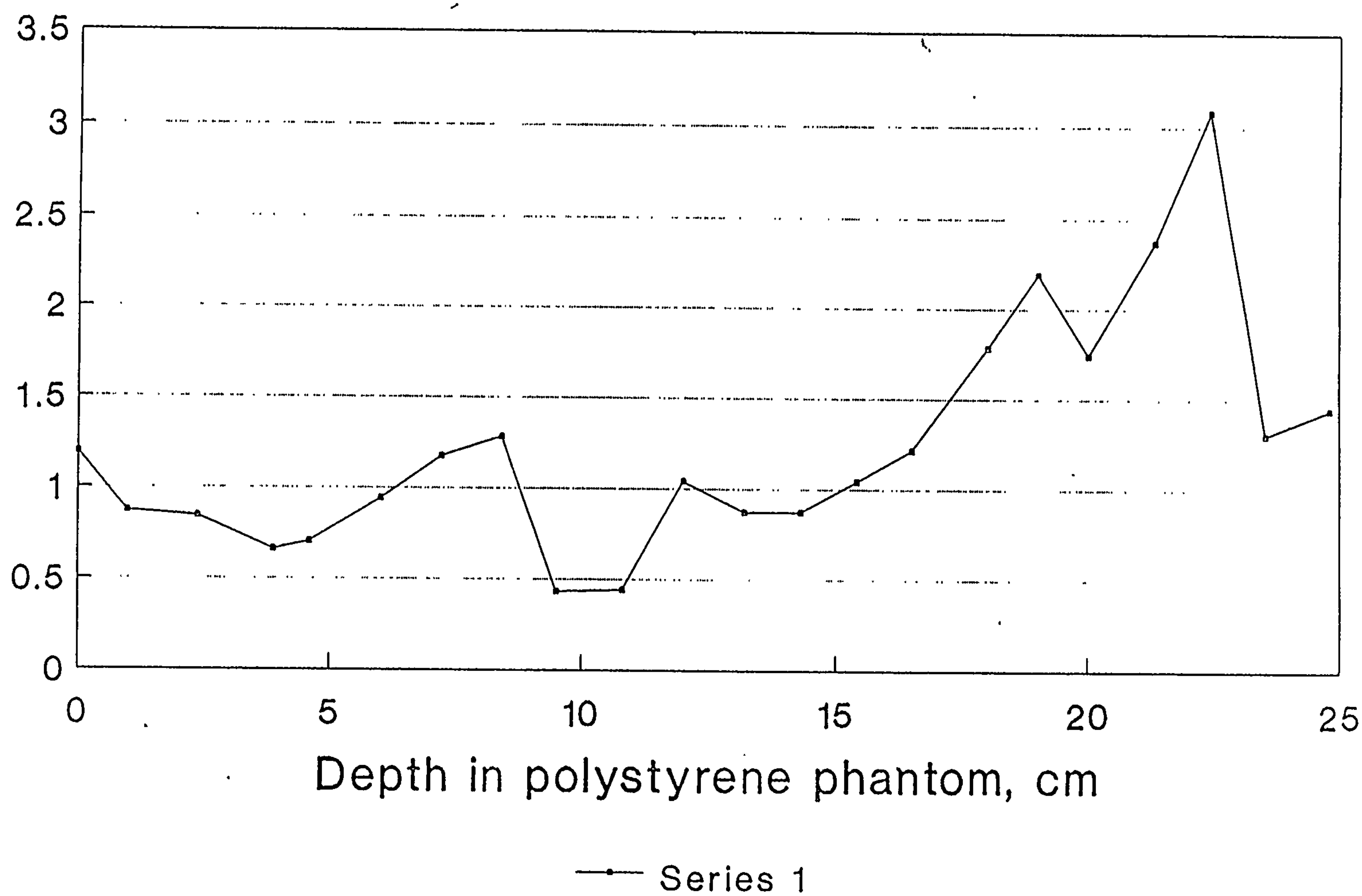
TLD700 Depth Dose Curve



TLD600 to TLD700 Ratio



CR-39 to TLD600 Dose Ratio



APPENDIX H

Memo from M. M. C. Torres to M. J. Robinet dated May 25, 1993

ARGONNE
NATIONAL
LABORATORY

INTRA-LABORATORY MEMO

May 25, 1993

To: M. J. Robinet — Section Head, ESH-HP

From: M. M. C. Torres — ESH-HP

Subject: *Update of IPNS Incident, Dose Assessment*

The total effective dose equivalent using weighting factor from ICRP 26 was calculated, 9.25 x 10^{-2} rem/min. In this case the quality factor used for neutrons was 11.8 and 1 for gamma so the TEDE = [11.8 x Dn(rad/min) + Dγ(rad/min) x 1] x Wt can be found through this previous expression. Also, the same calculation was done using ICRP 60 weighting factor and the effective dose found was 1.16 x 10^{-1} rem/min (see Table 1).

Another way of approaching the problem is to consider the average quality factor for the mixed field (neutrons plus gamma) 8.2, so the total effective dose equivalent is given by the expression TEDE = [8.2 (Dn + Dγ] x Wt and it is equal to 1.14 x 10^{-1} rem/min under ICRP 26 guidance. If ICRP 60 guidance is taken into consideration the effective dose is 1.58 x 10^{-1} rem/min (see Table 2).

Table 3 shows the calculation of the total dose for the bone marrow. Attachment 1 discusses the measurement of the quality factor performed at IPNS Phoenix Line for direct beam exposure. Table 4, Columns 1 and 2 show the measurements made with a tissue equivalent and a magnesium chamber in a 16 cm^3 water phantom as a function of depth.

Columns 3 and 4 show measurements made with TLD's 600 and 700 respectively in terms of light output per minute on different depths of slab #25 of the Randon Female Phantom. Column 5 shows the ratio of TLD (600-700) over tissue equivalent chamber (light output/rad) and Column 6 shows the ratio of TLD 700 over magnesium chamber (light output/rad) as a function of depth.

Figure 1 shows the plots of the above ratios as a function of depth.

Figure 2 shows the scan in 16 cm^3 of water with a tissue equivalent and magnesium chamber as a function of depth for direct beam exposure in Phoenix Line at IPNS.

MMT/cs

cc: File

Rando Female Dose Calculation

Organ or Tissue	TLDn Light output/min	TLD gamma Light output/min	Dn rad/min	Dg rad/min	Depth	Wt ICRP60	Eff. Dose (rem/min)	Wt ICRP 26	T.E.D.E (rem/min)
Brain	4.2	0.65	4.00E-05	8.33E-04	7.4	0.005	6.53E-06		
Tyroid	9.35	0.55	1.11E-04	6.96E-04	4.5	0.05	1.00E-04	0.03	6.02E-05
Esophagus	8.35	0.45	9.30E-05	5.92E-04	9	0.05	8.45E-05	-	
Thymus	9.2	0.4	1.53E-04	5.54E-04	2.4	0.005	1.18E-05	0.03	7.08E-05
Lung	22	0.7	2.20E-04	8.86E-04	6.8	0.12	4.18E-04	0.12	4.18E-04
Liver	416	5.85	4.62E-03	7.22E-03	5.6	0.05	3.09E-03	0.03	1.85E-03
Spleen	217	2.8	3.74E-03	3.94E-03	2	0.005	2.40E-04	0.03	1.44E-03
Pancreas	667	10.9	9.81E-03	1.45E-02	2.7	0.005	6.51E-04	0.03	3.91E-03
Kidney and Adrenals	329	5.3	5.13E-03	7.40E-03	10.2	0.01	6.79E-04	0.06	4.08E-03
Stomach	2651	43	3.37E-02	5.60E-02	3.7	0.12	5.44E-02	0.03	1.36E-02
Skin	1179	16	3.93E-02	2.54E-02		0.01	4.89E-03	-	
Small and Large int.	624	8.9	7.93E-03	1.16E-02	3.6	0.01	1.05E-03	0.06	6.31E-03
Ovaries	1030	6.7	1.91E-02	1.00E-02	11	0.2	4.71E-02	0.25	5.88E-02
Colon	22.6	0.75	6.35E-04	1.42E-03	13	0.12	1.07E-03	-	
Uterus	47.5	1.1	6.04E-04	1.43E-03	3.5	0.005	4.28E-05	-	
Bladder	32.1	0.95	3.77E-04	1.20E-03	4.8	0.05	2.82E-04	-	
Breast	9.6	0.7	3.20E-04	1.11E-03		0.05	2.44E-04	0.15	7.33E-04
Eyes	4.5	4	1.50E-04	6.35E-03					0.00E+00
Bone Marrow	*	*	7.24E-04	1.66E-03	*	0.12	1.22E-03	0.12	1.22E-03
Eff. Dose							**1.16E-01**		**9.25E-02**
	Qn=11.8	Qg=1							
	* see Bone Marrow								
	calculation								

Table 1

Female Phantom Qn,g8.2

Organ or Tissue	TLDn Light output/min	TLD gamma Light output/min	Dn rad/min	Dg rad/min	Depth	Wt ICRP60	Eff. Dose (rem/min)	Wt ICRP 26	T.E.D.E (rem/min)
Brain	4.2	0.65	4.00E-05	8.33E-04	7.4	0.005	3.58E-05		
Tyroid	9.35	0.55	1.11E-04	6.96E-04	4.5	0.05	3.31E-04	0.03	1.99E-04
Esophagus	8.35	0.45	9.30E-05	5.92E-04	9	0.05	2.81E-04	-	
Thymus	9.2	0.4	1.53E-04	5.54E-04	2.4	0.005	2.90E-05	0.03	1.74E-04
Lung	22	0.7	2.20E-04	8.86E-04	6.8	0.12	1.09E-03	0.12	1.09E-03
Liver	416	5.85	4.62E-03	7.22E-03	5.6	0.05	4.85E-03	0.03	2.91E-03
Spleen	217	2.8	3.74E-03	3.94E-03	2	0.005	3.15E-04	0.03	1.89E-03
Pancreas	667	10.9	9.81E-03	1.45E-02	2.7	0.005	9.97E-04	0.03	5.98E-03
Kidney and Adrenals	329	5.3	5.13E-03	7.40E-03	10.2	0.01	1.03E-03	0.06	6.16E-03
Stomach	2651	43	3.37E-02	5.60E-02	3.7	0.12	8.83E-02	0.03	2.21E-02
Skin	1179	16	3.93E-02	2.54E-02		0.01	5.31E-03	-	
Small and Large int.	624	8.9	7.93E-03	1.16E-02	3.6	0.01	1.60E-03	0.06	9.61E-03
Ovaries	1030	6.7	1.91E-02	1.00E-02	11	0.2	4.77E-02	0.25	5.97E-02
Colon	22.6	0.75	6.35E-04	1.42E-03	13	0.12	2.02E-03	-	
Uterus	47.5	1.1	6.04E-04	1.43E-03	3.5	0.005	8.34E-05	-	
Bladder	32.1	0.95	3.77E-04	1.20E-03	4.8	0.05	6.47E-04	-	
Breast	9.6	0.7	3.20E-04	1.11E-03		0.05	5.86E-04	0.15	1.76E-03
Eyes	4.5	4	1.50E-04	6.35E-03					0.00E+00
Bone Marrow	*	*	7.24E-04	1.66E-03	*	0.12	2.35E-03	0.12	2.35E-03
Eff. Dose							1.58E-01		1.14E-01
	Qn,g=8.2								
	* see Bone Marrow								
	calculation								

Table 2

Bone Marrow Dose Calculation

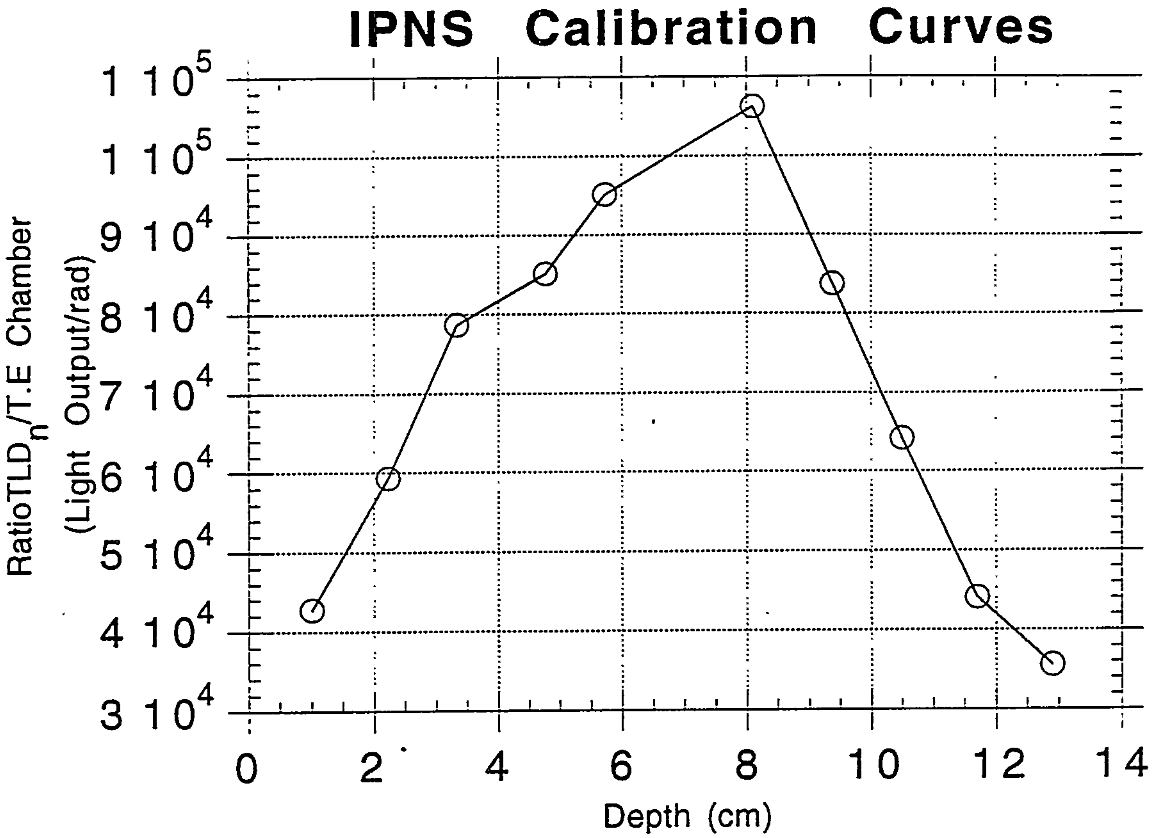
Organ or Tissue	TLDn Light output/min	TLD gamma Light output/min	Dn rad/min	Dg rad/min	Depth	Bone Marrow Distribution	Dn rad/min	Dg rad/min
Bone Marrow/Abdomen	26	0.85	3.33E-04	1.10E-03	3.4	0.47	1.57E-04	5.17E-04
Bone Marrow/Thorax	165	28	1.83E-03	3.68E-03	8.7	0.31	5.67E-04	1.14E-03
Total Dose Bone Marrow							**7.24E-04**	**1.66E-03**
Reference: External Dosimetry Technical Basis Manual								
WSRC-92-101								
January 15,1992								

Table 3

Slab#25 IPNS Randon Female Phan

Depth (cm)	T.E(rad/min)	Mg(rad/min)	TLDn(light/min)	TLDg(Light/min)	TLDn/T.E	TLDg/Mg
1.11	0.088	0.06	3759	40.6	42716	677
2.22	0.072	0.061	4269	56.4	59292	925
3.33	0.057	0.063	4482	48.4	78632	768
4.76	0.039	0.058	3319	46	85103	793
5.72	0.028	0.05	2664	41.1	95143	822
8.1	0.015	0.035	1593	26.9	106200	769
9.37	0.014	0.031	1172	23.3	83714	752
10.5	0.014	0.031	898	22.2	64143	716
11.7	0.013	0.029	572	17..8	44000	614
12.9	0.012	0.027	427	14.3	35583	530

Table 4


IPNS Calibration Curves
RatioTLD$_n$/T.E Chamber
(Light Output/rad)
1 10^5
1 10^5
9 10^4
8 10^4
7 10^4
6 10^4
5 10^4
4 10^4
3 10^4
0
2
4
6
8
10
12
14
Depth (cm)

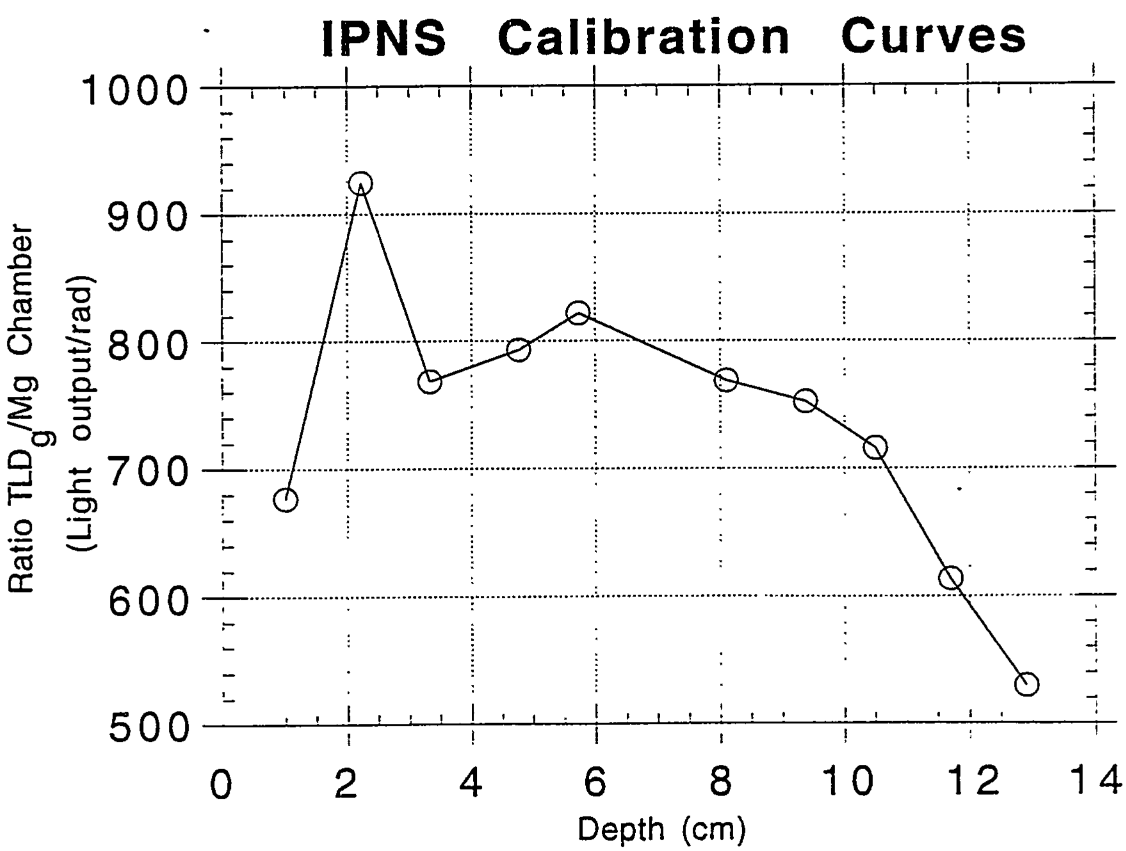
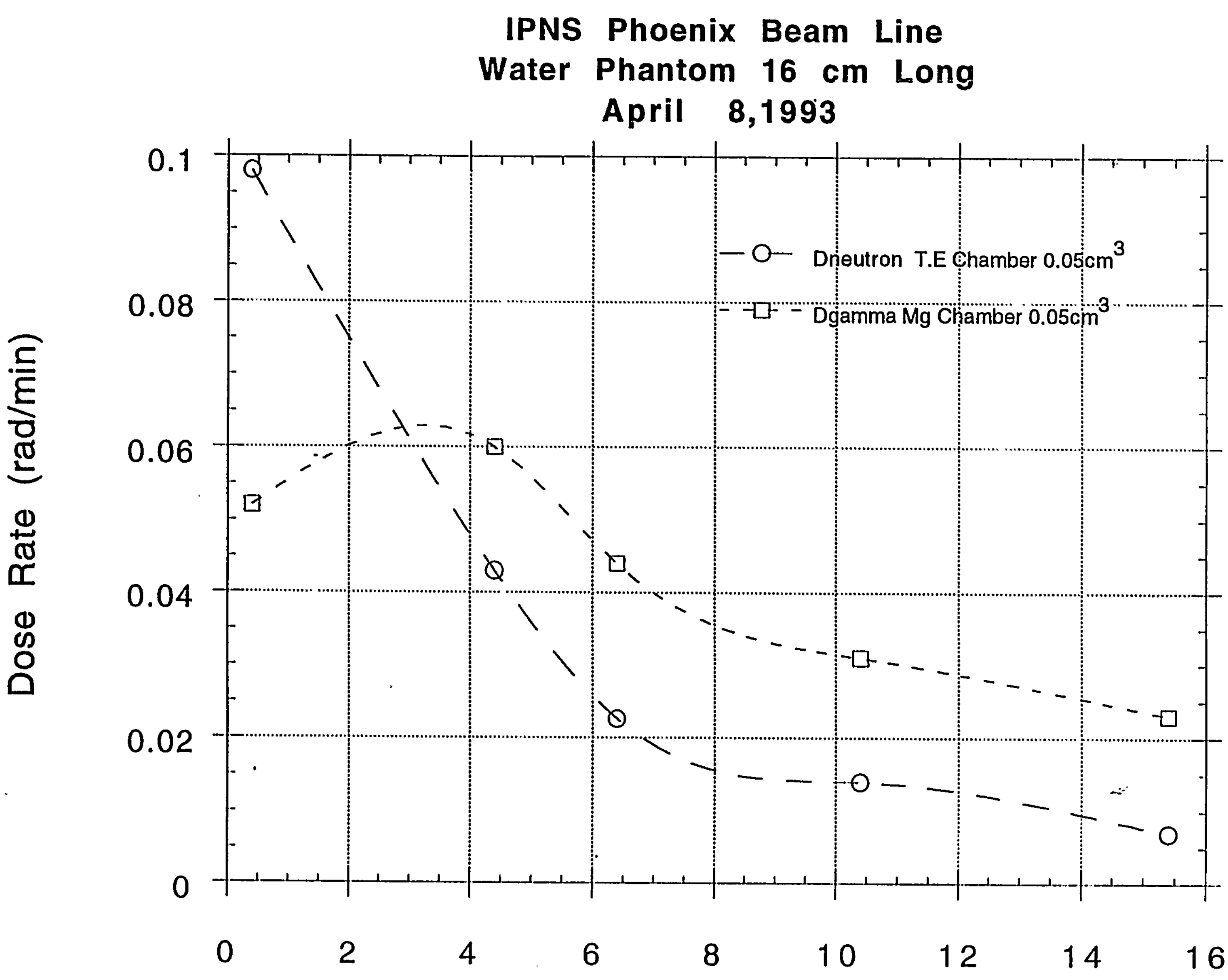

IPNS Calibration Curves
Ratio TLD$_g$/Mg Chamber
(Light output/rad)
1000
900
800
700
600
500
0
2
4
6
8
10
12
14
Depth (cm)

Figure 1


IPNS Phoenix Beam Line
Water Phantom 16 cm Long
April 8,1993
Dneutron T.E Chamber 0.05cm3
Dgamma Mg Chamber 0.05cm3
Dose Rate (rad/min)
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
12
14
16
Position (cm)
Figure 2

Attachment 1

Quality Factor Measurements

A recombination chamber was used at IPNS to measure the quality factor in Phoenix Beamline in direct beam exposure.

The average quality factor measured for mixed fields neutrons plus gammas is 8.2 ± 25%. The quality factor for neutrons is 11.8 ± 25%.

Linear Fit (see Figure 1)

$N = 4.32 \times 10^{-2} + 1.47 \times 10^{-2}\ QF$

N = 0.1634 (see Figure 2)

$\overline{QF} = 8.2 \pm 25\%$	mixed field neutrons plus gammas

The quality factor for neutrons can be obtained from the expression below

$$\overline{QF} = \frac{Dn\ Qn + D\gamma\ Q\gamma}{Dn + D\gamma}$$

$$8.2 = \frac{0.1\ Qn + 0.05 \times 1}{0.15}$$

$Qn = 11.8 \pm 25\%$

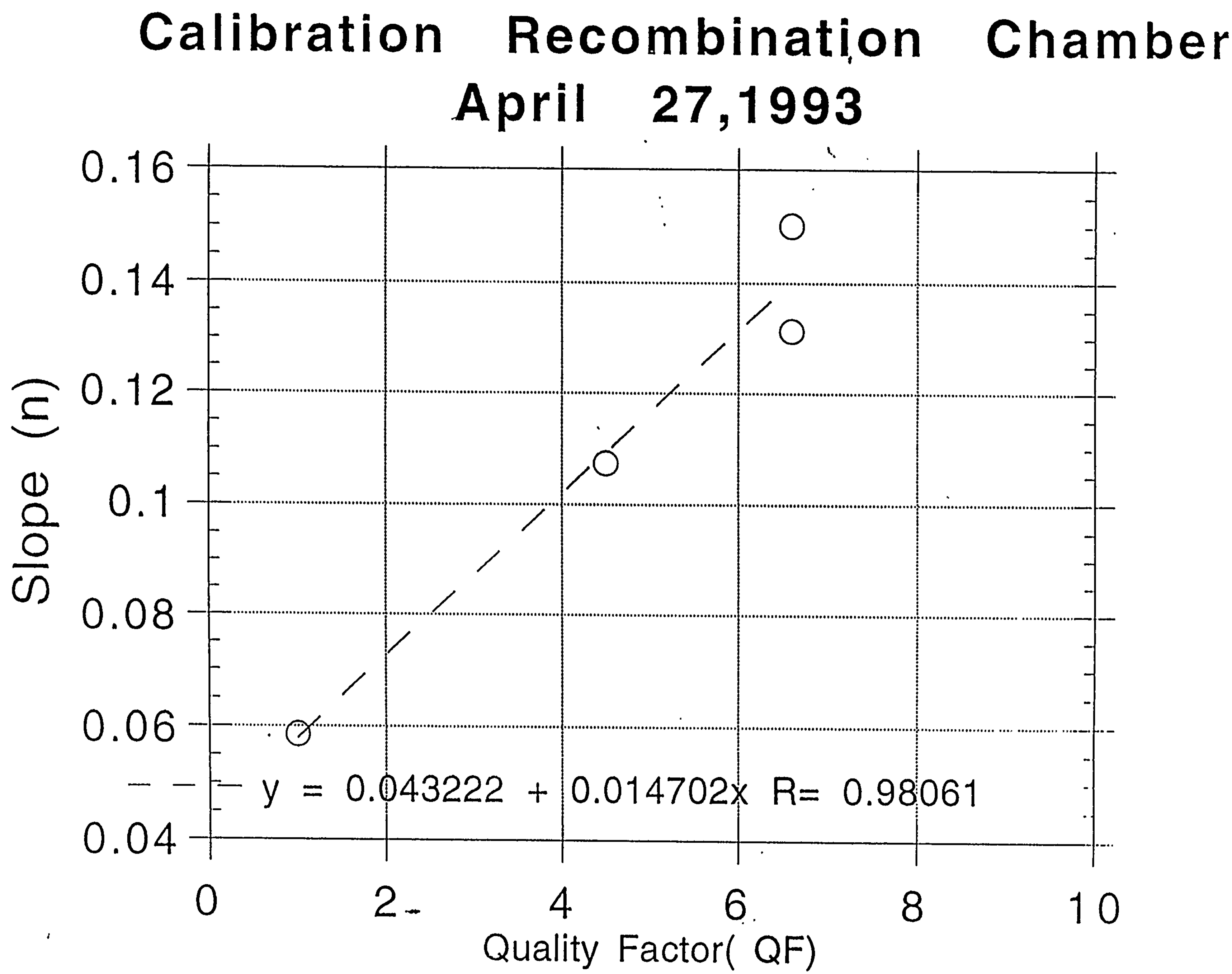

Calibration Recombination Chamber
April 27,1993
Slope (n)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
y = 0.043222 + 0.014702x R= 0.98061
0
2
4
6
8
10
Quality Factor(QF)

Figure 1

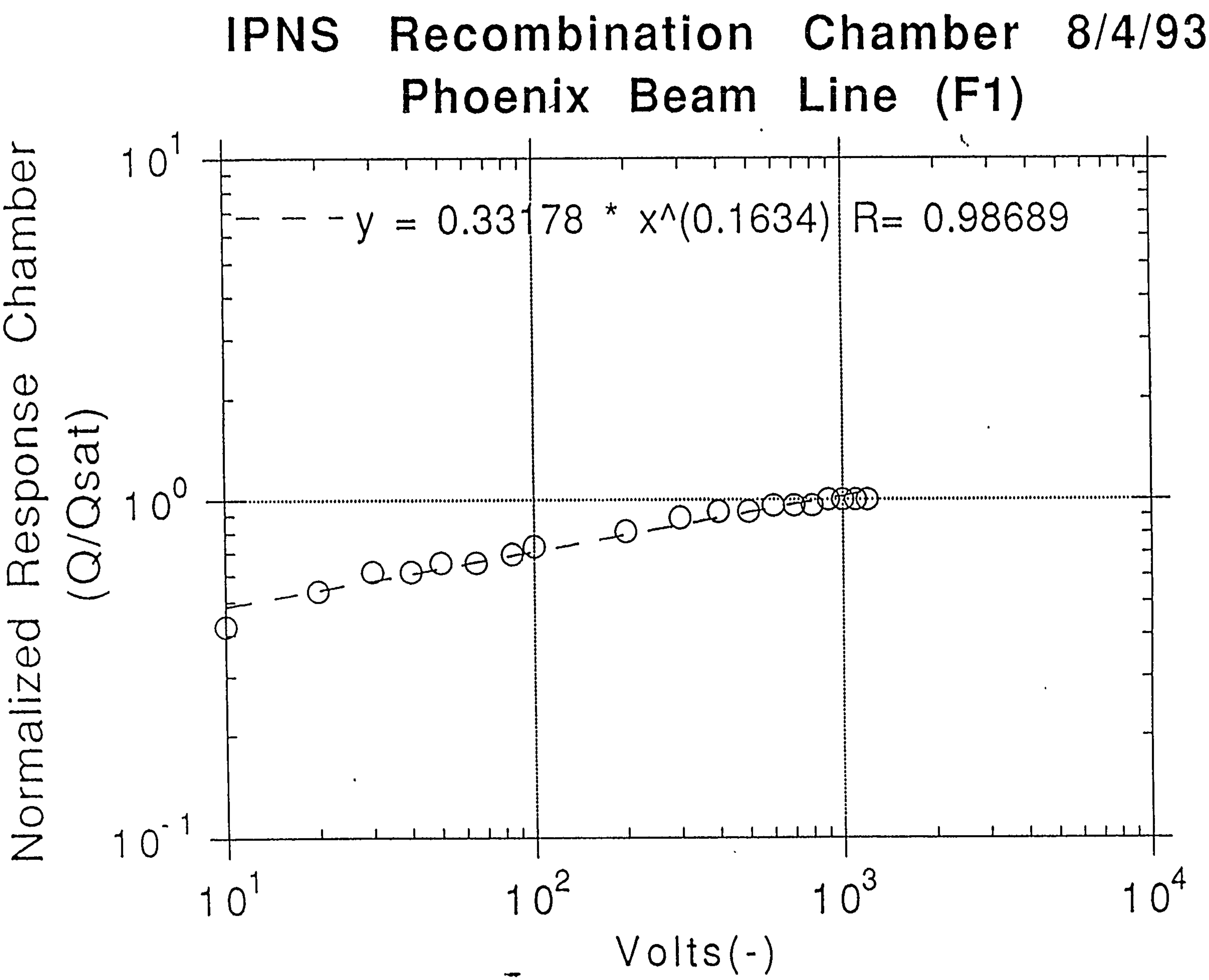

IPNS Recombination Chamber 8/4/93
Phoenix Beam Line (F1)
- - - y = 0.33178 * x^(0.1634) R= 0.98689
Normalized Response Chamber
(Q/Qsat)
10^1
10^0
10^-1
10^1
10^2
10^3
10^4
Volts(-)

Figure 2

APPENDIX I

Memo from R. A. Wynveen to B. S. Brown dated May 4, 1993

ARGONNE
NATIONAL
LABORATORY

INTRA-LABORATORY MEMO

May 4, 1993

To: B. S. Brown IPNS

From: R. A. Wynveen ESH

Subject: "DOSE" TO WORKER IN IPNS INCIDENT

While we are still receiving some final data and are further refining our interpretations of the wealth of data that has been accumulated relevant to the dose reconstruction activity associated with the IPNS exposure, we wish to indicate that a total effective dose equivalent rate of approximately 400 mrem/min can be used as a preliminary number for putting things into perspective. This number is of course subject to any refinements that may be necessary as a result of the data still being interpreted. Viewing the videotape reconstructing the incident indicates that the subject's torso was in the beam for approximately 4 minutes and that some part of her body (torso, shoulder, arm, etc.) was in the beam for approximately 4 minutes and 45 seconds. The dose equivalent to the ovaries appears to be of the order of 140 mrem/min.

ESH plans to develop an extensive report which will document the definition of the "problem," provide the approach to developing the "dose of record," summarize the data and include the results, conclusions and appropriate discussion. Assistance from representatives of BIM, Fermilab, and PNL, as well as others, is acknowledged and appreciated.

RAW.llc

cc: H. Drucker
F. Y. Fradin
R. J. Teunis
File (RAW)

bcc: D. C. Parzyck
M. J. Robinet
R. A. Schlenker
R. E. Toohey
M. M. C. Torres
E. H. Dolecek

APPENDIX J

Battelle Report - Effective Dose Equivalents in a Female Anthropomorphic Phantom Exposed to the IPNS PHOENIX Beamline dated May 1993

Battelle
Pacific Northwest Laboratories
Battelle Boulevard
P.O. Box 999
Richland, Washington 99352
Telephone (509) 375-2024

May 21, 1993

Mr. McLouis J. Robinet
Argonne National Laboratory
Building 201
9700 South Cass Avenue
Argonne, IL 60439

Dear Mac:

Enclosed is a report describing our calculations of the effective dose equivalent and organ dose equivalents for a female anthropomorphic phantom exposed to radiation from the IPNS PHOENIX beamline.

If you have any questions, please feel free to contact me at the above number. It has been a pleasure working for you.

Sincerely,

Robert D. Stewart
Research Scientist
Dosimetry Research Section
HEALTH PHYSICS DEPARTMENT

RDS/ag

Enclosure

Battelle
Pacific Northwest Laboratories
Battelle Boulevard
P.O. Box 999
Richland, Washington 99352
Telephone (509) 375-2024

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Argonne National Laboratory
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Sincerely,

Robert D. Stewart
Research Scientist
Dosimetry Research Section
HEALTH PHYSICS DEPARTMENT

RDS/ag

Enclosure

Evaluation of Effective Dose Equivalents in a Female Anthropomorphic Phantom Exposed to the IPNS PHOENIX beamline.

by

R. D. Stewart and J.E. Tanner

Battelle Pacific Northwest Laboratory
May 1993

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Introduction

At the request of Argonne National Laboratory, the Pacific Northwest Laboratory has calculated neutron and gamma dose rates to a female anthropomorphic phantom exposed to ionizing radiation from the IPNS PHOENIX beamline. Neutron and gamma fluences were calculated for organs distributed throughout the phantom with the Monte Carlo neutron/photon transport code MCNP (MCNP, 1988). These fluences were then used to evaluate organ doses, organ dose equivalents and the effective dose equivalent for spectra characteristic of the PHOENIX beamline.

Effective Dose Equivalent

The concept of effective dose equivalent was introduced in 1977, by the ICRP in Publication 26, Recommendations of the ICRP. ICRP 26 defined weighting factors for specific organs and tissues based on the absolute risk coefficients for the induction of a fatal malignant disease (see Table 1). The risk coefficient for the gonads also includes ***serious*** genetic defects that occur in the first two generations of offspring. The effective dose equivalent is defined as the sum of the weighted dose equivalents to the specified organs and tissues. This can be expressed mathematically as

$$H_E = \sum_T w_T H_T \qquad (1)$$

where H_E = effective dose equivalent, H_T = dose equivalent for a specific organ or tissue (T) and W_T = weighting factor for a specific organ or tissue (T).

ICRP 26 weighting factors are not gender specific and include risks associated with both the male and female organs. The current ICRP 26 methodology specifies weighting factors for the gonads, breast, red bone marrow, lung, bone surfaces, and thyroid (refêr to Table 1). An additional weighting factor is defined for the ***remainder***. The ICRP recommends that a value of 0.06 is applicable to each of the five organs or tissues of the remainder (i.e., an organ other than the six specifically identified above) receiving the highest dose equivalents, and that the exposure of all other remaining tissues can be neglected. One difficulty with the ICRP's definition for the remainder is that the effective dose equivalent is not necessarily additive because different organs may be used to define the remainder for different source energies and irradiation geometries.

Table 1. ICRP 26 and female specific weighting factors for the effective dose equivalent.

Tissue	ICRP 26 Risk (Sv^{-1})	ICRP 26 W_T	Female Risk (Sv^{-1})	Female W_T
Ovaries	40×10^{-4}	0.25	40×10^{-4}	0.21
Breast	25×10^{-4}	0.15	50×10^{-4}	0.26
Red Bone Marrow	20×10^{-4}	0.12	19×10^{-4}	0.10
Lung	20×10^{-4}	0.12	19×10^{-4}	0.10
Bone Surfaces	5×10^{-4}	0.03	6×10^{-4}	0.03
Thyroid	5×10^{-4}	0.03	8×10^{-4}	0.04
Remainder	50×10^{-4}	0.30	50×10^{-4}	0.26
Total	165×10^{-4}	1.00	192×10^{-4}	1.00

In the present work, the female specific weighting factors listed in Table 1 are used (Burger 1981) to compute the effective dose equivalent. The organs used to define the remainder have also been fixed, so that the effective dose equivalent is directly additive. If the organs that comprise the remainder are fixed, the additive property of the effective dose equivalent is valid for all internal and external exposures, including non-uniform (partial) exposures. For the calculations reported here, the remainder consists of the stomach, small intestine, upper and lower large intestines, and the trunk (NOTE: ICRP 26 states that when the gastro-intestinal tract is irradiated, the stomach, small intestine, upper large intestine, and lower large intestine are treated as four separate organs).

Definition of the effective dose equivalent as a weighted sum of the organ dose equivalents is attractive because it can account for the different radiosensitivities of organs and tissues distributed throughout a body. Further, calculations based on an anthropomorphic phantom will provide much less conservative estimates of the effective dose equivalent than the simpler neutron fluence-to-dose-equivalent conversion factors embodied in the ICRU operational quantities (ICRU, 1977, 1985, 1988).

Irradiation Geometry

Effective dose equivalent and organ dose equivalent data were calculated in an idealized anthropomorphic phantom adapted from the German developed phantom EVA (Kramer et al. 1982). A frontal view of the phantom is pictured in Figure 1.

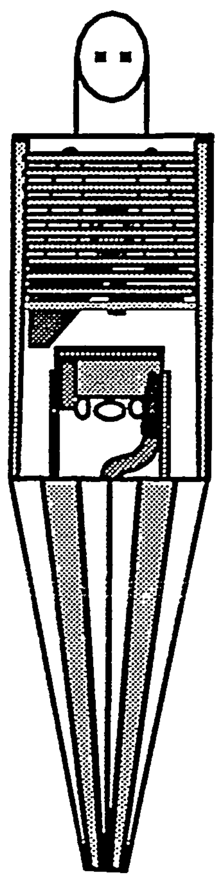

Figure 1. Frontal view of the female anthropomorphic phantom.

A female worker was exposed to a 1 x 2 inch rectangular beam of ionizing radiation from the PHOENIX beamline. The radiation was incident on the worker at about the level of her belly button or about the level of her ovaries pictured in Figure 1. The incident radiation was modeled as a 1 x 2 inch rectangular parallel beam of neutrons incident on the phantom. This should provide reasonable estimates of the dose rates, even if the radiation exhibits some angular spreading with increasing distance from the beam port, which would tend to decrease the (maximum) tissue doses directly in the beamline.

Source Spectra

Although a calculated neutron spectrum for the PHOENIX beamline was provided by R.K. Crawford (see Figure 2 and Appendix A), ion chamber measurements of the neutron dose rates in the beamline were used to corroborate the absolute magnitude (i.e., the normalization) of the incident fluence.

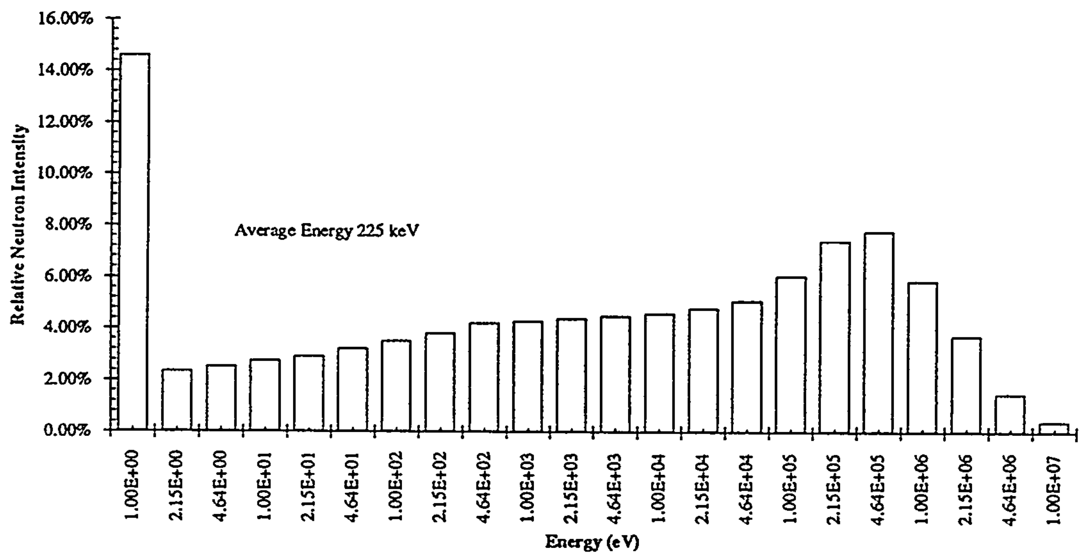

Figure 2. Calculated Neutron Fluence Produced by the PHOENIX Beamline (Crawford, 1993).

The average energy of the neutron spectrum calculated by Crawford neutron spectrum was 225.3 keV. The magnitude of the incident fluence was calculated by dividing the measured neutron dose rate (mrad/min) by a spectrum-averaged tissue kerma factor. The average tissue kerma factor for the PHOENIX beamline was computed as 5.180278×10^{-7} mrad cm^2, and this gave a neutron fluence of 1.8558×10^8 n/cm^2 s. In contrast, Crawford predicted the source normalization would be 6.1293×10^8 n/cm^2 s - a factor 3.3 higher. The spectrum-averaged neutron quality factor (Cross and Ing, 1984) for the PHOENIX beamline was calculated to be in the range of 9.15 to 9.18.

No calculated or measured spectra were available for the gamma-rays produced by the PHOENIX beamline. However, measurements of the gamma-ray attenuation in the beamline suggest that the average energy of the gamma-rays was approximately 1 MeV. Consequently, effective dose equivalent and organ dose equivalent calculations were performed for 0.5, 1.0, and 2.0 MeV monoenergetic gamma-ray beams incident on the phantom to give a range of plausible gamma dose rates. The magnitude of the incident gamma-rays was computed by a procedure similar to the one outlined for the neutron spectrum. Namely, the gamma dose rates measured with the ion chamber were divided by a tissue kerma factor for the different gamma-ray energies. The tissue kerma factors for the 0.5, 1.0, and 2.0 MeV gamma-rays are 2.62×10^{-7}, 4.93×10^{-7}, and 8.28×10^{-7} mrad cm^2, respectively. This resulted in fluences for 0.5, 1.0, and 2.0 MeV gamma-rays incident on the phantom of 1.97×10^8, 1.05×10^8, 0.624×10^8 γ/cm^2 s, respectively.

Results of Calculations

Neutron Dose Rates

MCNP was used to calculated the maximum tissue dose rates in a semi-infinite slab of tissue irradiated by a parallel beam of neutrons with the energies calculated by Crawford (refer to Appendix A). Table 2 shows a comparison of the calculated maximum tissue dose rates and ion chamber measurements. These data are also shown graphically in Figure 2.

If the spectrum provided by Crawford is not re-normalized to the ion chamber measurements (i.e., the Crawford flux curve in Figure 2), the calculated dose rates are higher than the ion chamber measurements for tissue depths up to about 5 cm and lower for greater tissue depths. The calculated tissue doses that were normalized to the ion chamber measurements (see the discussion in the Source Spectra Section) agree well with the ion chamber that was made free-in-air (i.e., at depth zero), but decrease much more rapidly than the ion chamber measurements. The different dose-depth response curves for the calculated and measured dose rates indicates that either the source neutron spectrum calculated by Crawford is not accurate (i.e., the PHOENIX spectrum is *harder* than the one calculated by Crawford), or the measurements to do not give a precise indication of neutron dose rates (this could be caused by difficulties associated with discriminating the gamma dose from the neutron dose, or by uncertainties associated with the instrument calibration).

Table 2. Measured and calculated neutron tissue doses (mrad/min) in the IPNS PHOENIX beamline.

Tissue Depth (cm)	Crawford Spectra Normalized to Measurement	Unmodified Crawford Spectra	Ion Chamber Measurement
0	100.53	204.74	96.13
1	79.00	160.90	80.53
2	55.04	112.09	67.46
3	38.37	78.14	56.51
4	27.35	55.70	47.34
5	20.07	40.87	39.65
6	14.94	30.43	33.22
8	8.77	17.86	23.31
10	5.46	11.12	16.36
12	3.49	7.12	11.48
14	2.31	4.70	8.06
16	1.57	3.19	5.65
18	1.10	2.23	3.97
20	0.73	1.50	2.78

Since it will be difficult to determine which calculated spectrum (i.e., which normalization) is more appropriate to the PHOENIX beamline, it would seem prudent to use the spectrum and normalization calculated by Crawford. This would give the most conservative estimates of the dose rates.

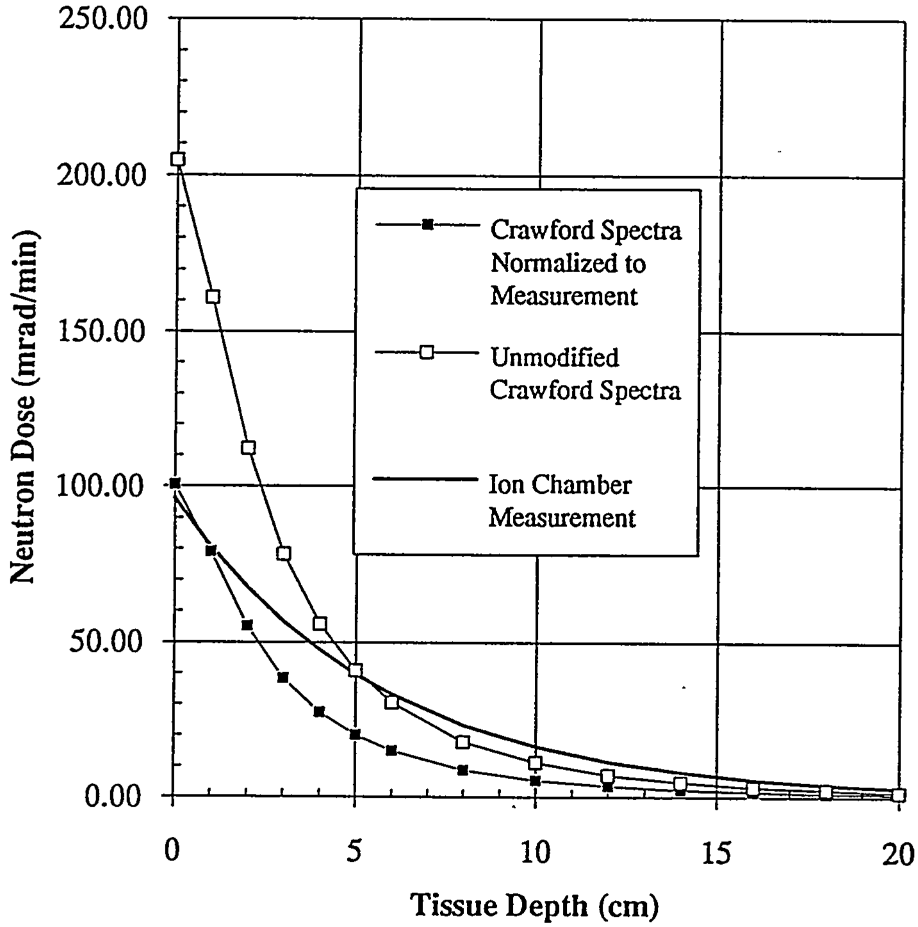

Figure 2. Maximum tissue absorbed doses (mrad/min) in the IPNS PHOENIX Beamline.

On the basis of the spectrum and normalization reported by Crawford, the neutron effective dose equivalent rate was determined to be 4.80 $\pm$ 0.03 mrem/min. The reported dose rate precision indicates the numerical precision of the calculation and does not include any uncertainties associated with the differences between the actual radiation worker and the idealized phantom used for these calculations. Appendix B gives a complete listing of the organ doses, organ dose equivalents, and quality factors for the Crawford spectrum. Appendix C lists the same information listed in Appendix B, but for the Crawford spectrum normalized to the ion chamber measurements.

Gamma Dose Rates

Since no direct information was available for the gamma component of the PHOENIX beamline, a series of monoenergetic gamma dose calculations was performed. Measurements of the gamma attenuation suggest that the gamma component of the beamline had an average energy of about 1 MeV. Consequently, Monte Carlo dose calculations were performed for 0.5, 1.0 and 2.0 MeV as a plausible indicator of the dose rates produced by the gamma component of the radiation field. The gamma effective dose equivalent rates were 0.4096 ± 0.0007, 0.4341 ± 0.0005, 0.4476 ± 0.0005 mrem/min., respectively.

Conclusions

Monte Carlo Calculations were performed for a female worker exposed to ionizing neutrons and gamma-rays produced in the IPNS PHOENIX beamline. Because only a small fraction of her body was exposed to the ionizing radiation, the calculated effective dose equivalent is a factor of 20 lower than the maximum tissue dose rates. The best (and most conservative) estimate for the neutron dose rate was 4.80 mrem/min, and the gamma dose rate is likely to be in the range of 0.40 to 0.45 mrem/min.

The discrepancies between ion-chamber measured neutron tissue doses and calculated tissue doses indicates an unresolved discrepancy between the calculated neutron spectrum and the spectrum suggested by the ion chamber measurements. It would be difficult to resolve this problem without significant additional calculations and measurements. However, it seems reasonable to believe that any differences in the spectrum would not change the dose rates by more than a factor of 2 (e.g., compare the dose rate calculations in Appendix B and C).