Fermilab

Addendum to:

Radiation Physics Note No. 135

DOSE ASSESSMENT AT BODA

Initial Issue: January 2000

Revision 1: December 2013

Revision History

Author	Description of Change	Revision No. and Date
Matthew Quinn	Addendum added to incorporate radiation dosimetry system modifications implemented by June 2007 amendments to 10 CFR 835. The details are explained in the Addendum.	Revision 1, December 2013
Elaine Marshall and Alex Elwyn	Original issue	Revision 0, January 2000

December 2013 Revision Approval

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INTRODUCTION TO THE ADDENDUM

In June 2007, the Department of Energy modified its Federal Regulation, 10 CFR Part 835, *Occupational Radiation Protection*, to incorporate the use of a more modern system of radiation protection dosimetry set forth by the International Commission on Radiation Protection (ICRP) beginning in the early 1990s in ICRP Reports 60, 68, 74, and, most recently 103. The modified radiation protection dosimetry initially applied only to occupational radiation protection considerations. More recently, in February 2011, the updated system of radiation protection dosimetry was extended to environmental radiological conditions with the issue of DOE Order 458.1, *Radiation Protection of the Public and the Environment*. The purpose of this addendum is to clarify how to use the approximation method set forth in the original RP Note to obtain results that are expressed in the new radiological units. The new units are those that are to be used to evaluate radiological exposures and design new facilities in conformance to the current DOE-approved Radiation Protection Program (RPP) for Fermilab.

MODIFICATIONS TO THE RESULTS OF THE ORIGINAL NOTE

The original version of this Note contains the results of study of the dose delivered to frozen turkeys thawed before irradiation at the Neutron Therapy Facility (NTF) at Fermilab. The irradiations were done both in the direct neutron beam and off the beam axis. The dose delivered at both positions was measured with a tissue-equivalent ionization chamber already in place at NTF. The irradiated turkeys were then counted at BODA to check the validity of the dose estimate contained in Ref. A1. LiF TLD and CR39 dosimeters were also placed on the front and back of each turkey.

The measurements at BODA contained in the original version of this Note were done with a Bicron Analyst and a NaI detector. Both measurements determined the absorbed dose of the turkeys in units of mrad from the production of activation products within the turkey carcasses. Therefore, these measurements are unaffected by the change in dosimetry required by 10 CFR 835.

While the dosimeters from the direct beam turkeys were unreadable due to high doses, the off-axis dosimeters gave dose equivalent values that corresponded to a *quality factor*, Q of 2.3. At the time of writing the original version of this Note, the specifically-defined quantity *dose equivalent* was that specified by 10 CFR 835 to be used to measure personnel doses and compare them against regulatory standards, such as those contained within 10 CFR 835 and in DOE Order 458.1. Dose equivalent remains a valid radiation protection dosimetric quantity. However to be consistent with the newer radiation protection system as implemented in 10 CFR 835 and the Fermilab RPP, one needs to obtain results in units of *effective dose*, as explained more elaborately in Ref. A2. In this new system the quality factor is replaced with a *radiation weight factor* w_R.

The original Note concluded that the off-axis NTF radiation field is dominated by neutrons with energies below 20keV, based on a comparison of NTF neutron energy spectrum measurements reported in Ref. A3 and Ref. A4.

Cossairt and Vaziri[A2] have analyzed the effects of the modifications to the DOE system of radiation dosimetry upon neutron spectroscopy measurements and calculations of radiation fields typical to Fermilab produced by high energy protons. They include a table of calculated w_R values for various energies using the formula contained in ICRP report 103. For 20keV, w_R is 3.92, while below 5keV w_R is 2.5.

Therefore to convert the dose equivalent determined in the original version of this Note to effective dose in a conservative manner, the quality factor of 2.3 should be replaced with a radiation weight factor of 4. The absorbed doses listed in the original Note are connected to the effective dose through the equation:

$$H_{eff} = w_R D$$

where H_{eff} is the effective dose, w_R is the radiation weight factor, and D is the absorbed dose in rads.

Additionally, on page 3 of the original Note in section 3, there is an erroneous reference to ^{13}Ni, this should instead be ^{13}N.

REFERENCES TO THE ADDENDUM

A1 C. Salsbury and A. Elwyn, Dose Estimates at the Beam-On Dose Assessment Facility, Fermilab Rad. Phys. Note #85 (1990).

A2 J. Donald Cossairt and Kamran Vaziri, "Neutron Dose per Fluence and Weighting Factors for Use at High Energy Accelerators", Health Physics 96 (2009) 617-628.

A3 V.R. Cupps, A.J. Elwyn, A.J. Lennox, and T.Kroc, "Fermilab NTF Neutron Beam Energy Spectrum by Foil Activation." Poster Session Radiation Research Society 44th Annual Meeting, Chicago, IL. April 14-17, 1996.

A4 H.W. Patterson and R.H. Thomas, Accelerator Health Physics, p.71, Academic Press, New York and London, 1973.

Fermilab
ES&H Section

RP Note 135

DOSE ASSESSMENT AT BODA-I

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January 2000

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RP Note 135

DOSE ASSESSMENT AT BODA-I

E. Marshall and A. J. Elwyn
January 2000

1. Introduction

The Beam-On Dose Assessment (BODA) facility at Fermilab was established to allow for a dose estimate to be made rapidly following a beam-on exposure. A dose estimate within the first couple of hours after such an incident helps to determine the appropriate course of action in treating the victim. For many years, the procedures used (Sa90) have been based upon work performed in the prompt radiation fields at Brookhaven National Laboratory (Di73) and Lawrence Berkeley National Laboratory (Mi72). They reflect, therefore, the characteristics of the composition and spectra of the fields at those institutions. While the prompt fields at BNL and LBNL are likely to be similar to those fields at Fermilab, they are not necessarily identical. This study represents the first of a series of investigations to review the beam-on dose assessment procedures in light of the different properties of the various radiation fields at Fermilab. This paper discusses the results of measurements performed at the Neutron Therapy Facility (NTF), where neutrons with energies up to 66 MeV are used for patient treatment.

2. Experimental Set-up

Frozen turkeys, bought at local food stores, were allowed to thaw out and then irradiated in the collimated[1] neutron beam at the isocenter (the location at which patients are usually treated) in the NTF facility, and also exposed to the ambient neutron field in the room during the direct irradiation. Fig.1 shows the experimental setup. Turkeys were used in these measurements because it was thought that their composition reflects human tissue more closely than does, say, a water phantom. In the first two runs at irradiation times of 1 and 5 minutes, only turkeys were used. In the third run at an irradiation time of 2.5 minutes both turkeys and five-gallon plastic carboys (a cylinder 11.5 inches in diameter and 15 inches high) filled with water were irradiated. The carboys were studied to determine whether water could be an appropriate substitute for tissue for beam-on exposure studies.

The monitoring equipment - a tissue-equivalent ionization chamber - already in place at NTF was sufficient to determine the radiation dose received by the in-beam turkey or carboy. For the off axis measurements in the ambient neutron field, both a NTF 1-cc

[1] The collimator was installed in the upstream end of NTF and produced a 10 cm by 10 cm beam at the isocenter.

tissue equivalent ion chamber and a Scarecrow ion chamber were positioned as indicated in Fig. 1 to determine the absorbed dose at that location. In calibration runs the two detectors were intercompared at the two positions and found to give results in excellent agreement with each other when in the same location. In the measurements, the final dose at the position of the off-axis turkey or carboy was taken as the average of the readings of the two detectors. For the 1 and 5 minute irradiations the on-axis turkey received dose at a uniform rate of 40 and 41rads/min respectively, and at an irradiation time of 2.5 minutes the rate was 44 rad/min. Off axis, the dose rates were 260 mrad/min at 1 minute, 247 mrad/min at 5 minutes, and 280 mrad/min at the 2.5 minute exposure.

The counting instruments at the BODA consist of a (Modified) Bicron Analyst GM survey meter and an 8" by 2" NaI(Tl) detector. At all irradiation times, the electronic deadtimes associated with the NaI detector and circuitry were too high to allow the determination of residual counting rates for the in-beam irradiation of both turkeys and carboys even at post-irradiation times of one hour. For the off-axis (scattered beam) irradiation residual counting rates were too small in the Bicron to provide statistically useful data. Thus, only turkeys and carboys irradiated off-axis were analyzed with the NaI detector, and the Bicron was used only for the in-beam irradiations. All data were corrected for the dead time of the instruments, and the net counts per minute (cpm) discussed below has been corrected for background. The measurements with the Bicron were started within 1 – 2 minutes after the end of the exposures; those with the NaI were initiated 15 – 20 minutes post exposure. The counting rates for the NaI detector were determined for all counts above about 0.1-MeV on the pulse height gamma-ray spectrum.

3. Discussion

Studies at BNL (Di73) and LBL (Mi72) demonstrated that the isotopes ^{15}O ($T_{1/2}$=2.03 minutes), ^{13}Ni ($T_{1/2}$=9.96 minutes), and ^{11}C ($T_{1/2}$=20.4 minutes) dominate the radioactivity within the body in the first few hours after exposure in a hadron beam. Thus, the activity B (in Bq, e.g.) can be written

$$B = \lambda_{11}N_{11} + \lambda_{13}N_{13} + \lambda_{15}N_{15}, \qquad (1)$$

where N_{11}, N_{13}, and N_{15} are the number of atoms of each isotope produced in the irradiation, and λ_{11}, λ_{13}, and λ_{15} are the decay constants[2] of ^{11}C, ^{13}N, and ^{15}O, respectively. For induced radioactivity build-up in uniform pulsed beams (as at NTF), it was shown (Cu97) that, e.g. for ^{11}C,

$$\lambda_{11}N_{11} = \Phi\sum_j (n_j\sigma_{11,j})\left[\frac{(1-e^{-\lambda_{11}t_{on}})}{(1-e^{-\lambda_{11}t_p})}(1-e^{-\lambda_{11}pt_p})\right]e^{-\lambda_{11}t_d}. \qquad (2)$$

[2] The values are 0.034, .0696, and 0.341 min^{-1} for ^{11}C, ^{13}N, and ^{15}O, respectively.

Similar expressions can be written for ^{13}N and ^{15}O. The cross section $\sigma_{i,j}$ is that for the production of isotope i from reactions with element j in the body with n_j atoms. The sum is over all elements j that contribute to isotope production. Φ is the incident neutron flux in n/cm^2-sec.

For NTF, the beam pulse width t_{on} =57 μsec=9.5 x 10^{-7} min, the period t_p =1/15 Hz=0.0667 sec=1.11 x 10^{-3} min and, thus, the duty factor t_{on}/t_p = 8.55 x 10^{-4}. Then, irradiation (or exposure) time is t_a=p x t_p, where p=number of pulses during beam on. Since, p=t_{clock}/t_p then t_a=t_{clock}. As mentioned, turkey irradiations were performed at three clock times, 1 , 2.5, and 5 minutes, and the carboy irradiation was for 2.5 minutes.

In the expression for λN above, and with the values for the quantities associated with the NTF beam, λt_{on} and λt_p are both very much less than 1 and the first factor within the brackets can be replaced by t_{on}/t_p. Thus,

$$\lambda_{11} N_{11} = \Phi \frac{t_{on}}{t_p} \sum_j (n_j \sigma_{11,j}) \left[(1 - e^{-\lambda_{11} t_a}) \right] e^{-\lambda_{11} t_d}, \tag{3}$$

along with similar expressions for ^{13}N and ^{15}O. Writing

$$a_{11} = \sum_j n_j \sigma_{11,j}; a_{13} = \sum_j n_j \sigma_{13,j}; a_{15} = \sum_j n_j \sigma_{15,j},$$

the induced activity in the body can be expressed as:

$$B = \Phi \frac{t_{on}}{t_p} [a_{11}(1 - e^{-\lambda_{11} t_a}) e^{-\lambda_{11} t_d} + a_{13}(1 - e^{-\lambda_{13} t_a}) e^{-\lambda_{13} t_d} + a_{15}(1 - e^{-\lambda_{15} t_a}) e^{-\lambda_{15} t_d}]. \tag{4}$$

When the radioactivity saturates, after an irradiation time "long" compared to the longest half-life, $B \equiv B_s$, where

$$B_s = \Phi \frac{t_{on}}{t_p} [a_{11} + a_{13} + a_{15}]. \tag{5}$$

Therefore, we can write

$$B_s = \frac{B}{f(t_a, t_d)}, \tag{6}$$

where $f(t_a, t_d) = a_{11}^*(1 - e^{-\lambda_{11} t_a}) e^{-\lambda_{11} t_d} + a_{13}^*(1 - e^{-\lambda_{13} t_a}) e^{-\lambda_{13} t_d} + a_{15}^*(1 - e^{-\lambda_{15} t_a}) e^{-\lambda_{15} t_d}$, and

$a_{11}^{*} = \dfrac{a_{11}}{a_{11} + a_{13} + a_{15}}$, with similar expressions for a_{13}^{*} and a_{15}^{*}. Note that

$$a_{11}^{*} + a_{13}^{*} + a_{15}^{*} = 1. \qquad (7)$$

The readings in net counts per minute (cpm) M from both of the BODA survey instruments - the Bicron Analyst GM survey meter and the 8" by 2" NaI(Tl) detector - are each proportional to body activity. Thus, for either instrument,

$$M = k'B. \qquad (8)$$

From (5) above, flux Φ is proportional to the saturated activity B_s, and since the incident spectrum is assumed constant during irradiation, absorbed dose rate D_r is also proportional to B_s. And, because the survey meter readings are proportional to body activity at any time B, then, from (6) above,

$$D_r = k \frac{M}{f(t_a, t_d)}, \qquad (9)$$

where k is the calibration constant that relates absorbed dose rate to cpm readings on the instruments.

The constant k (rad/min per cpm) can be determined from the turkey irradiation data at the three irradiation times of 1, 2.5, and 5 minutes as follows: The background and dead time corrected cpm from each BODA detector M divided by the incident dose rates (rad/min) can, from (9)above, be written as

$$\frac{M}{D_r} = \frac{1}{k} f(t_a, t_d).$$

Plotting this quantity as a function of time after exposure t_d, and fitting the curve to a sum of exponential terms, as indicated in the expression for $f(t_a, t_d)$, the coefficients $k^{-1}a_i^{*}, i = 11,13,15$ can be determined. The individual coefficients a_i and the constant k can then be obtained from these by use of the equality expressed in (7).

4. Calibration and Dose Estimate for the Bicron Analyst

The quantity $\dfrac{M}{D_r}$ plotted as a function of minutes post-exposure t_d from the Bicron measurements is shown in Fig.2 at each of the three irradiation times. Also shown are the fits to the quantity $\dfrac{1}{k} f(t_a, t_d)$ leading to the coefficients $m_i = k^{-1} a_i$. In the fitting process, it was found that the inclusion of ^{13}N in the expression for activity was not necessary to describe the data. When it was included, the coefficient was quite uncertain; fits as good could be obtained with ^{11}C and ^{15}O alone.

Based on the coefficients $m_1 = k^{-1}a_{11}, m_2 = k^{-1}a_{15}$ we can determine the values of the coefficients a_i and the constant k, as discussed in the last section. The results are given in Table 1.

Table 1: Coefficients from Analysis of Bicron measurements. The last line represents average values.

Irradiation Time (min)	a_{11}^{*}	a_{15}^{*}	***k* (rads/min per cpm)**
1	0.323	0.677	1.45 x 10^{-4}
2.5	0.349	0.651	1.16 x 10^{-4}
5	0.3615	0.6385	1.60 x 10^{-4}
	0.345 ± 0.020	**0.655 ± 0.020**	**(1.38 ± 0.23) x 10^{-4}**

The calibration graph, Fig. 3, was constructed by calculating the total dose corresponding to a Bicron Analyst reading of 1 cpm for various exposure times t_a. That is, in Fig. 3,

$$A = 0.138 \frac{t_a}{f(t_a, t_d)} mrad / cpm .$$

Finally, then, for a given exposure time, A is found from the graph at the appropriate elapsed time after exposure, and the total dose (in mrad) can be determined by multiplying by the measured net cpm M. Thus,

$$D_T = A \times M .$$

We estimate that errors of 20-25% are to be associated with doses determined in this manner.

5. Calibration and Dose Estimate for the NaI Scintillation Detector

As with the Bicron analysis, the quantity $\frac{M}{D_r}$ from the measurements with the NaI detector plotted as a function of t_d is shown in Fig. 4 at each of the three irradiation times.[3] As with the BICRON analysis, the fits to these curves led to the determination of the coefficients a_i and the constant k. Because the measurements with the NaI detector did not start until 15-20 minutes post exposure, the exponential function associated with the 2-minute half life ^{15}O activity was excluded from the fit expression. In fact, except for the 5-minute irradiation, good fits to the data were found based on ^{11}C alone. For the 5-minute exposure an improved fit was obtained with the inclusion of the 10-minute ^{13}N activity along with that from ^{11}C. Based on the coefficients from the fits, shown in Fig. 4, the average calibration constant is

$$k = (6.29 \pm 1.30)x10^{-5} \quad \text{mrad/min per cpm.}$$

As above, the calibration graph for the NaI detector, shown in Fig. 5, was constructed by calculating the total dose corresponding to a reading of 1 (net) cpm for various exposure times t_a[4]. Thus, for NaI,

$$A = (6.29x10^{-5})\frac{t_a}{f(t_a,t_d)} mrad / cpm .$$

And, as above, for a given exposure time the constant A is found from Fig. 5 at the appropriate elapsed time post-exposure, and the total dose (in mrad) for a given net cpm M for the NaI detector is

$$D_T = AxM .$$

Again, errors are about 25%.

6. Carboy Irradiation Results

As mentioned above, two five-gallon plastic carboys filled with water were irradiated for a 2.5 minutes exposure time in order to determine whether the results from such irradiation are sufficiently similar to those from the turkeys that they can be used as substitutes in future irradiation studies. The results, compared to those for the turkeys, are shown in Figs. 6 and 7. As observed in Fig. 6 for NaI the two sets of measurements are in excellent agreement[5] in both magnitude and shape. The coefficient obtained from the fit to the quantity $\frac{1}{k} f(t_a,t_d)$ for the carboy is in agreement with that for the turkey within the rather small errors from the fit. Therefore, the carboy serves as an appropriate

[3] The data from the 1minute irradiation exhibited three "spuriously" large values at post exposure times between 27 and 33 minutes. These three points have been excluded from the plots.

[4] Although the 5-minute data, which included both the ^{11}C and the ^{13}N activities, were used in the present calibration to determine the conversion constant, the values for A were calculated with the expression for $f(t_a,t_d)$ that includes only the activity associated with 11C.

[5] There is some divergence at post exposure times of 50 minutes and more that is not understood.

substitute for a turkey in connection with studies performed in enclosures (but not in the direct beam), at least when analyzed with the NaI detector.

For the Bicron measurements, on the other hand, although the time dependence for the carboy results is well fit to the expression for $\frac{1}{k} f(t_a, t_d)$ with ^{11}C and ^{15}O as before for the turkey (see Fig. 7), the coefficients a^*_{11} and a^*_{15} have values of 0.451 and 0.549, different from those shown in Table 1 for the turkey. These values suggest that the contribution of ^{11}C to the total activity is about 30% larger for the carboy than for the turkey when measured with the Bicron detector. It should be recalled that the Bicron measurements were performed only on the turkey and carboy that were irradiated in the direct beam. It is likely therefore that, since the measurements were performed exactly at the location at which the irradiation occurred, the carbon in the plastic walls of the carboy may contribute more to the total carbon activity than does the activation of the carbon in the turkey itself. Unfortunately, no measurement of an empty carboy was performed to check its activation when not filled with water. Any future measurements at locations around the laboratory should include such determinations.

Further, as observed in Fig.7, the turkey response with the Bicron is about a factor of 3 times larger, on the average, than that for the carboy over the whole post-exposure time range. This can be understood qualitatively as due to differences in the volumes of the two "radiation sources" as viewed by the Bicron detector. As mentioned, the collimated beam that irradiated either the turkey or the carboy was about 4 inches by 4 inches, or 16 inches squared in cross sectional area. For the turkey, the volume irradiated and seen by the detector is, then, this area times the approximate thickness at the irradiation location (about 8 inches). For the water filled carboy, on the other hand, the source volume seen by the Bicron detector is the total volume of the carboy since the almost constant motion of the water spreads the radioactivity throughout. If the turkey is modeled as a "cylinder" of 8-inch length with the irradiation on the 16 inch squared cross sectional area "top" – the part surveyed with the Bicron – and the carboy as a cylinder, irradiated and viewed by the Bicron on the 15-inch long side, an estimate of the ratio of the response of the Bicron for the turkey to that for the carboy can be made. On the assumption that the specific activity due to beam irradiation is uniform throughout the source volumes for both, we find (see the Appendix) a value for this ratio of about 4.1, neglecting absorption in the media, and 3.6 if self-absorption is included. These values are in reasonable agreement with the observed ratio of about 3.

7. Dosimetry

During the 1 and 5 minute irradiations, Fermilab dosimeters consisting of LiF TLDs and CR39, were affixed to both the front and back of all the turkeys. For the turkeys exposed to the direct beam, all of the CR39 badges, those monitoring neutrons only, both front and back directly in line with the beam, were unreadable due to the very high incident doses (40-200 rads). For the off-axis irradiated turkeys, on the other hand, the CR39 badges on the side of the turkeys facing the isocenter irradiation position registered readings that gave averaged dose-equivalent values (in mrem) 2.3 (± 0.24) times the incident absorbed dose readings, measured as described in Section 2 above. This number therefore can be associated with the quality factor[6] for those neutrons that arise from scattering from the turkey at the isocenter, as well as from other parts of the room.

Cupps, et al (Cu96) measured the energy spectrum in the NTF neutron beam by a foil activation technique, and preliminary results suggest that the average neutron energy in the beam is 22 MeV, with a quality factor of 6.2. This number is, as it should be, in good agreement with the effective quality factor read from the curve in Patterson and Thomas (Pa73) for 20 MeV neutrons. Unfortunately, the measurements in Cu96 did not include room-scattered spectra, and comparisons with the quality factor suggested above by the present out-of-beam measurement can not be made. Suffice to say, however, that if energies below about 20 keV predominate in the room scattered neutron spectrum, then a quality factor for the neutron field with a value near 2 is reasonable (Pa73).

The TLD badge readings on the front of the turkeys facing the direct beam, those recording gamma radiation predominately, give an estimate, when compared to the incident absorbed dose due to neutrons, of the approximate gamma "contamination" of the incident neutron beam. For the 1 and 5 minute irradiation, the absorbed dose due to the gamma radiation is about 30% of the dose due to neutrons (determined by the NTF tissue equivalent ion chamber) alone. If the beam consists only of neutrons and photons, then based on the above dose measurements, about 23% of the particles in the incident beam are photons. This assumes, of course, that during the short time of beam irradiation of the turkeys, few gamma rays associated with the turkey radioactivation itself are recorded by the badges.

8. Summary

It is unfortunate that the Bicron Analyst and the 8" x 2" NaI detector used at the BODA could not each be employed to survey both the directly irradiated turkeys (and carboys) as well as those exposed to the ambient neutron field. Such measurements would have allowed a more complete investigation and comparison than has been presented here. While it seems likely that the carboy can serve as an appropriate substitute for a turkey when surveyed with both instruments under both direct and ambient field irradiation, it has not been definitely determined on the basis of the present studies.

Even so, dose estimates based on an accidental exposure in the neutron fields at NTF can be obtained from measurements with both the Bicron and NaI detectors at the appropriate post-exposure time by use of the curves shown in Figs. 3 and 5, and the methods outlined in this report.

[6] One should perhaps take this "measurement" of the quality factor with a measure of skepticism since it is based on the dose equivalent determined from a Landauer algorithm associated with their badge calibration technique.

It is emphasized though that the results presented here for exposure in the neutron fields at NTF should not replace the procedures currently set up for use in a beam-on accident associated with operation of the high-energy accelerators - the Booster, Main Injector and the Tevatron - at the Lab. It is important that other measurements be performed at enclosures associated with these machines in order to refine the current BODA procedures.

9. Acknowledgements

It is a pleasure to acknowledge the help of Fred Krueger and Tom Kroc in setting up the detectors and in running the accelerator in the performance of these measurements, and the able assistance of Kathy Graden and Sue McGimpsey in taking the data. We also thank Arlene Lennox, the head of the NTF, for allowing us the time for these studies and for useful conversations.

10. References

Cu96 V.R. Cupps, A.J. Elwyn, A.J. Lennox, and T.Kroc, "Fermilab NTF Neutron Beam Energy Spectrum by Foil Activation." Poster Session Radiation Research Society 44th Annual Meeting, Chicago, Il., April 14-17, 1996.

Cu97 V. Cupps and A. Elwyn, "Induced ^{11}C Activity Buildup in Uniform Pulsed Beams." Internal Report Radiation Physics Note # 130, Fermi National Accelerator Laboratory, Batavia, Il., September 1997.

Di73 C.H. Distenfeld, R.D. Colvett, and J.A. Ash, "Evaluation of Accidental Exposure to Accelerator Personnel." Health Physics & Safety Division Informal Report, Brookhaven National Laboratory, Upton, N. Y., April 1973.

Ja68 R.G. Jaeger (editor-in-chief), "Shielding Fundamentals and Methods." Engineering Compendium on Radiation Shielding, Vol. I, Springer-Verlag, New York 1968.

Mi72 A.J. Miller and H.W. Patterson, "Measurement of Induced Activity to Estimate Personnel Radiation Exposures Received from Accelerator Beams." Health Physics 23, 671 (1972).

Pa73 H.W. Patterson and R.H. Thomas, Accelerator Health Physics, p.71, Academic Press, New York and London, 1973.

Sa90 C. Salsbury and A. Elwyn, "Dose Estimates at the Beam-On Dose Assessment Facility." Internal Report Radiation Physics Note # 85, Fermi National Accelerator Laboratory, Batavia, Il., April 1990.

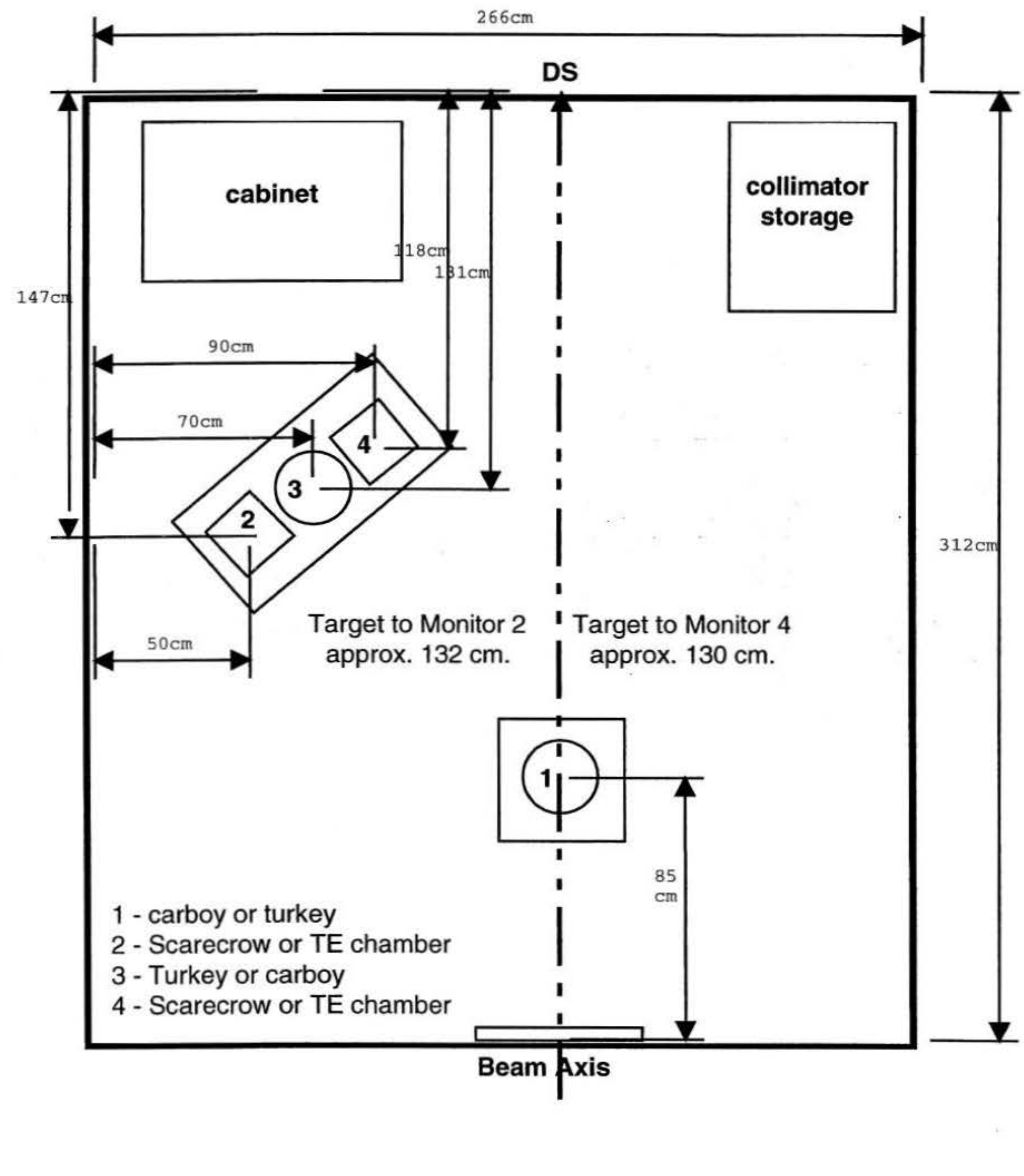

Figure 1. NTF Layout for BODA Turkey Irradiation Study. (We are indebted to Fred Krueger for this figure).

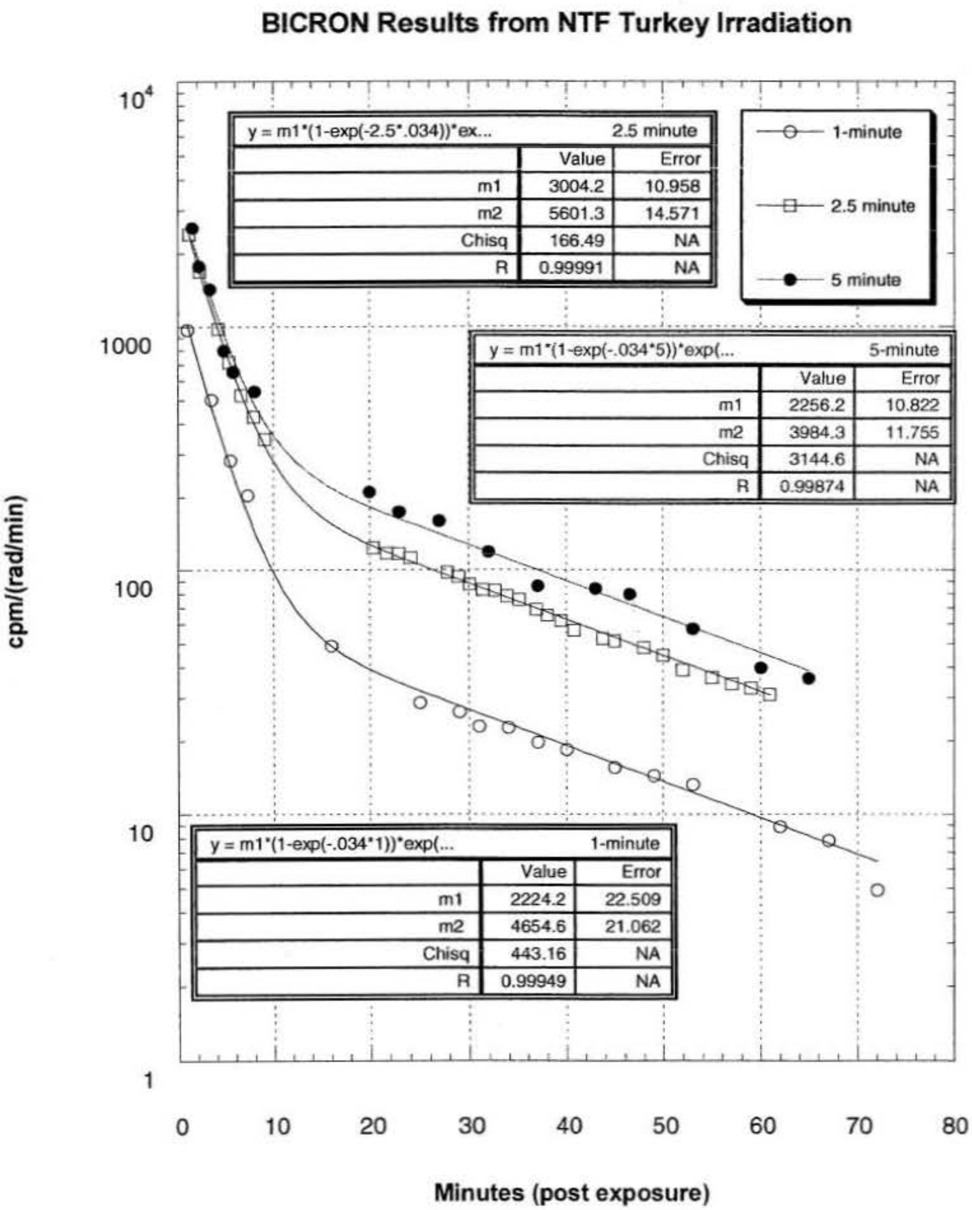

Figure 2. Results with the modified BICRON from the NTF Turkey Irradiation.

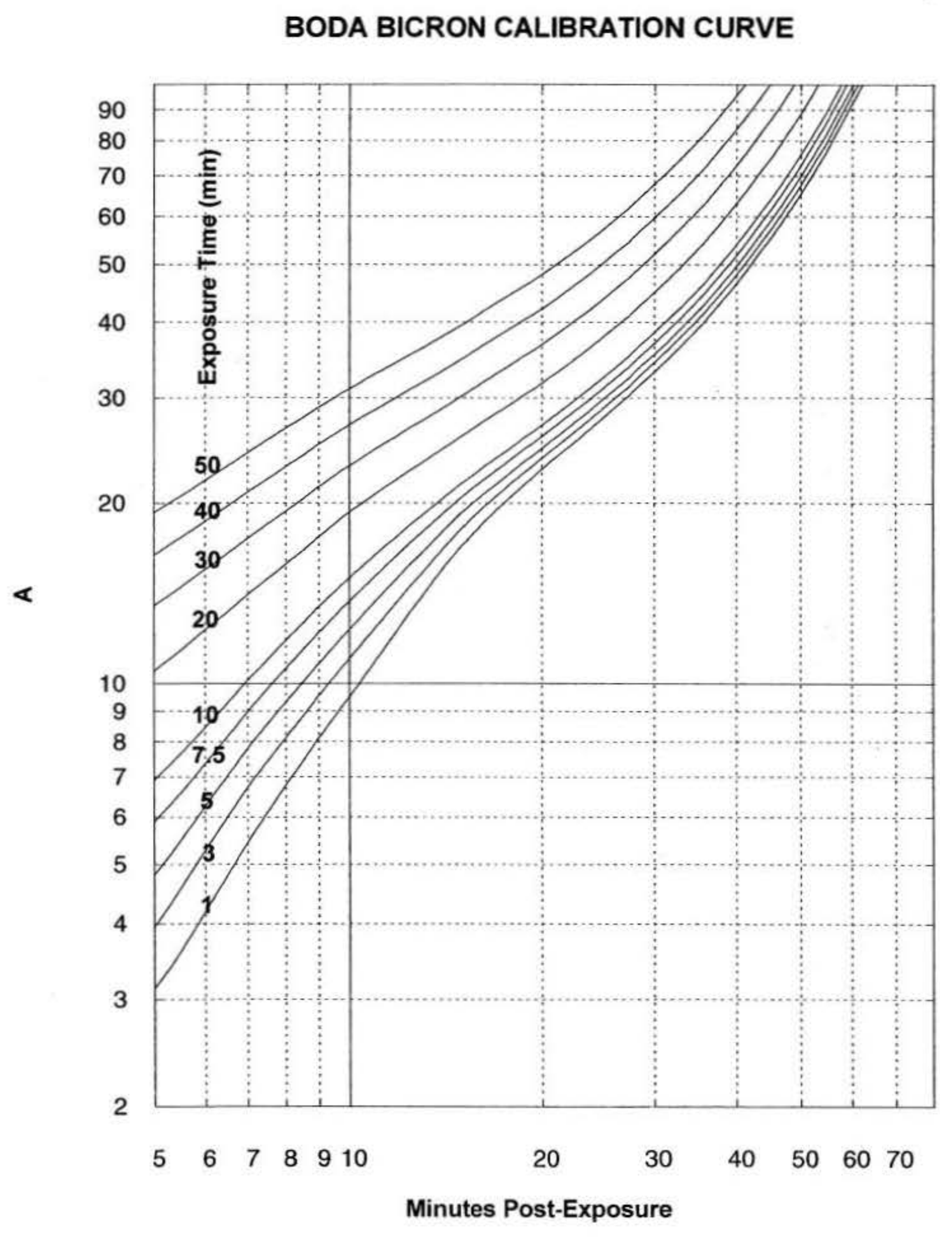

Figure 3. Calibration Curve for the Modified BICRON Detector.

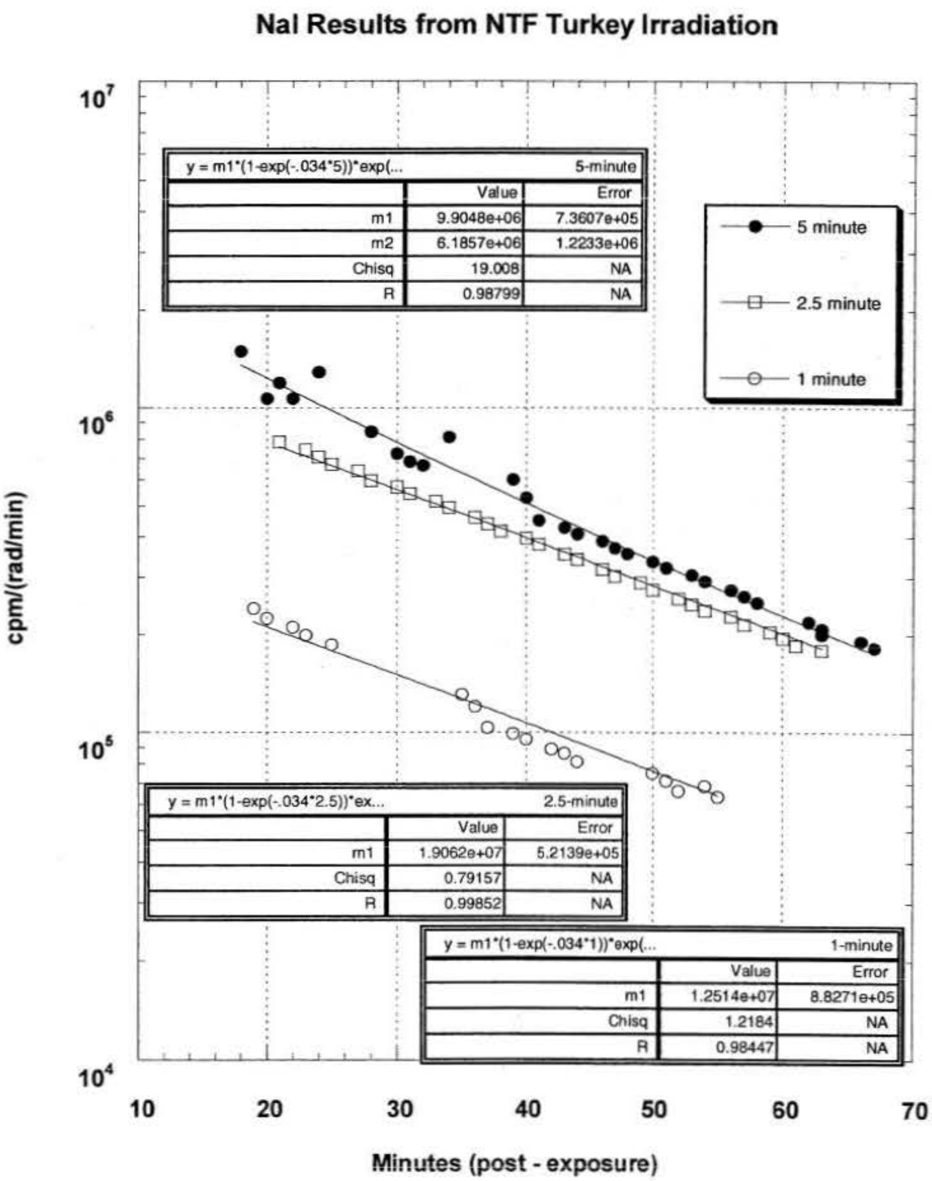

Figure 4. Results from the NaI Detector for the NTF Turkey Irradiation. The cpm are for all spectral counts above 0.1-MeV.

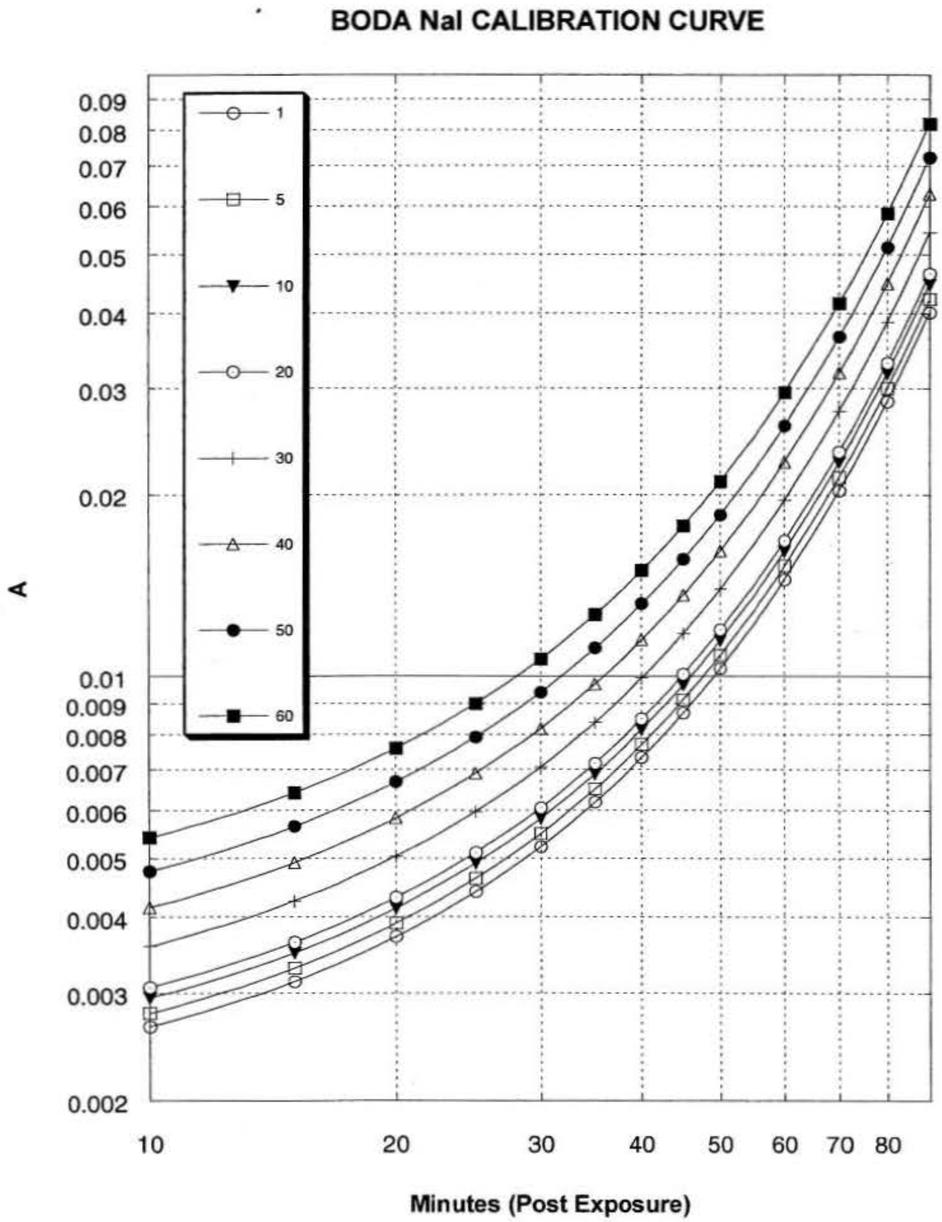

Figure 5. Calibration Curve for the BODA NaI Detector. The legend shows the symbols that represent curves associated with various exposure times (in minutes).

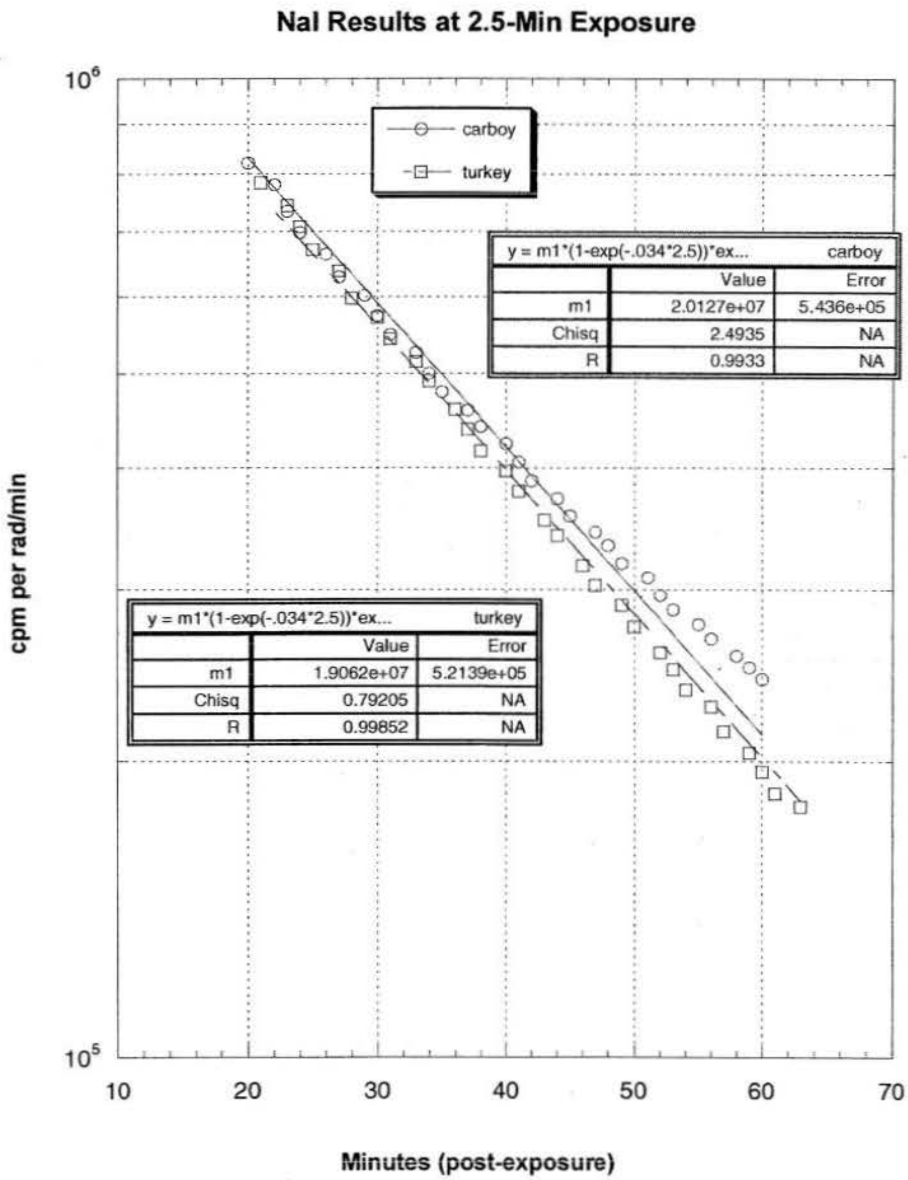

Figure 6. Comparison of the response of the NaI detector at the BODA for the turkey and the carboy at a 2.5 minute exposure time.

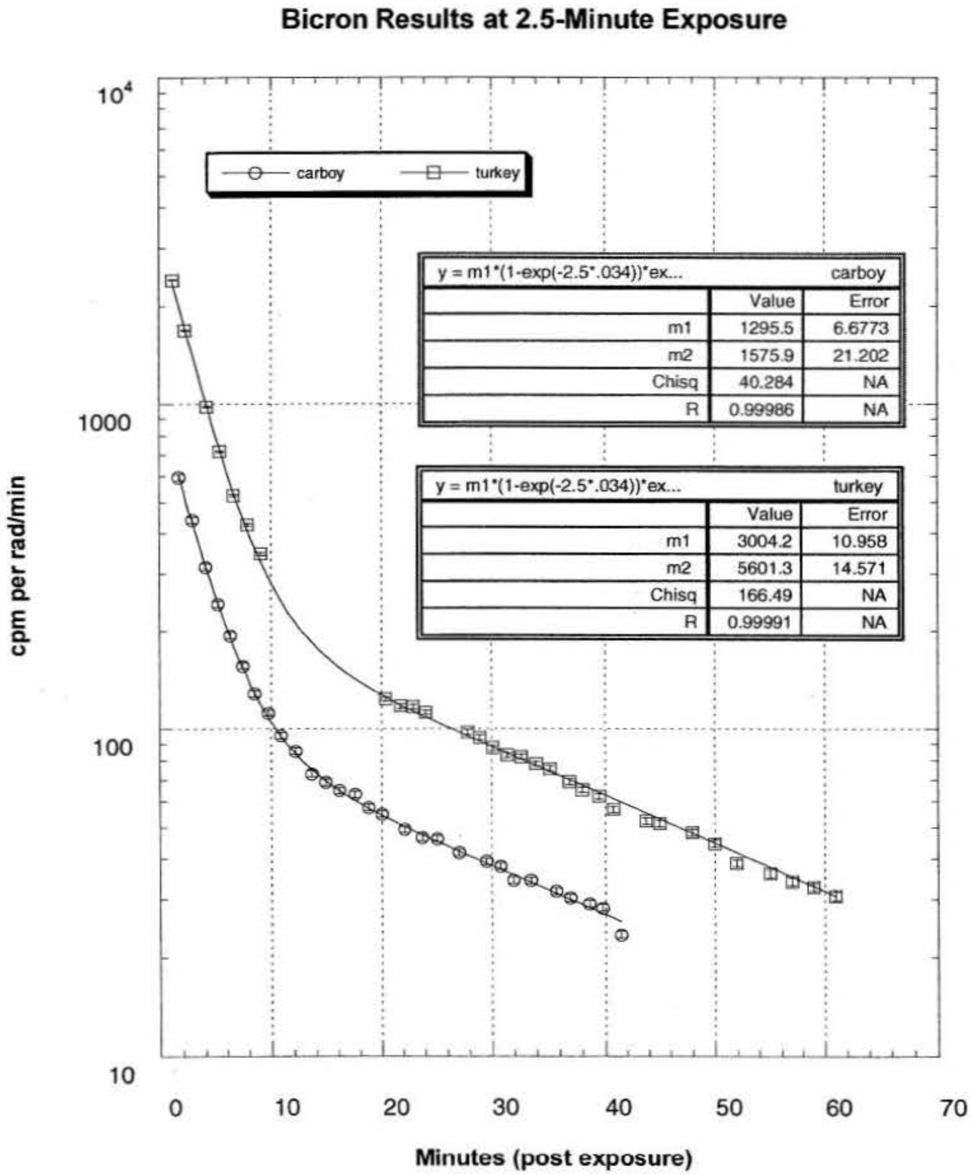

Figure 7. Comparison of the response of the modified Bicron detector for the turkey and the carboy at a 2.5 minute exposure time.

APPENDIX

The neutron beam at the isocenter of the NTF therapy room has dimensions of 4 in by 4 in, or 16 in^2. The irradiated turkey is assumed to be a cylinder 8 inches in length with a radius of 2.5 inches[7] at the "top face" where the beam strikes it. The carboy is taken as a cylinder 15 inches in height and a radius of 5.75 inches, with the beam impinging on the long side. Because it is filled with water which "sloshes around" the total irradiated volume is taken as the volume of the carboy itself, not just the volume at the location of beam irradiation. Both the turkey and the carboy can be taken as cylindrical volume sources of radiation after being exposed in the neutron beam.

The Engineering Compendium on Radiation Shielding (Ja68) gives expressions for the gamma ray flux densities at various points on the exterior of a cylindrical radiation source. On the assumption of uniform specific activity and non-absorbing source media, expressions (6.4-20) and (6.4-26) (in Ja 68) allow the calculation of the fluxes Φ for the turkey and carboy, respectively. In the case of self-absorbing source media, expressions (6.4-33) for the turkey and (6.4-34a) for the carboy (in Ja68) should be used. For the self-absorption case gamma ray linear attenuation coefficients are given in Ch. 4 (Ja68). (See especially Table 4.1-5).

The ratio of Bicron counting rates in the turkey to that in the carboy is given by

$$\frac{C_{turkey}}{C_{carboy}} = \frac{\Phi_{turkey}}{\Phi_{carboy}} \cdot \frac{V_{carboy}}{V_{turkey}},$$

where **V** is the activated volume of the source. The results, using the expressions suggested above, give ratios of turkey to carboy counts equal to 4.9 for non-absorbing and 4.4 for absorbing media. If one further assumes that the turkey contains 20% water, so that its effective volume is assumed to be 20% larger than indicated above, then these ratios become 4.1 and 3.6, respectively.

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[7] This is the equivalent radius of a cylinder with the front face having an area of 16 in^2.