Radiation Control Group Note

93-12

Accidental Radiation Exposure

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Summary:

As a result of questions raised by ARR-2 reviewers (Nisy Ipe and Larry Coulson) about accidental exposure to radiation from electron beams and/or electron beams, I have briefly described a method of dosimetry and a means of evaluating the dose equivalent from two accident situations. This RCG Note will form the technical basis for a Radiation Control Operating Procedure for RCG Staff to cope with such an accident, suggestions to CEBAF Medical Services regarding a relationship with a local hospital and consideration of the REACTs Center at Oak Ridge National Lab for detailed dose evaluation and treatment.

Robert May

Two accident scenarios are proposed:

1) Radiation Exposure: beam in a shielded (~1 TVL) thick target of intermediate Z

High Power operations in the North Linac stub Test Dump at 400 MeV, 200 microAmps will produce a fast (>0.1 MeV) neutron fluence rate of 2×10^4 $n \cdot cm^{-2} \cdot sec^{-1}$ through the installed steel shielding at one meter and perpendicular to beam travel. The fast portion of the neutron spectrum is comprised of approximately 80% of the total neutron dose equivalent in this spectrum. If the fast neutron fluence rate and spectrum can be determined, the dose to localized areas and critical organs of the body can be determined. The photon exposure is <10% of the neutron dose at this location.[1]

One method of determining the fast neutron fluence is to measure the phosphorus-32 in hair samples from the $^{32}S(n,p)^{32}P$ reaction which has a 2.8 MeV threshold. This can be done by collection, digestion and co-precipitation of the ^{32}P from a one gram hair sample from various portions of the body[2]. A quantitative analytical determination ^{32}P can be performed with the RCG's (Canberra HT-1000,) hemispherical gas proportional chamber.

The activity can be related neutron fluence by $F = \dfrac{AW}{\sigma s M \lambda}$

where F = fast neutron fluence detected by sulphur activation ($n\ cm^{-2}$)
A = activity per gram of hair (dis min^{-1} per gram at t = 0)
W = atomic weight of sulphur (32000 mg $mole^{-1}$)
σ = activation cross-section of sulphur (225×10^{-27} cm^2 $atom^{-1}$)
s = sulphur content per gram of hair (45±3 mg g^{-1})
M = Avogadro's number (6.02×10^{23} atoms $mole^{-1}$)
λ = decay constant (3.67×10^{-5} min^{-1})

This method has a minimum sensitivity of 3.17×10^8 $n \cdot cm^{-2}$ or approximately 15 rem based upon a 1 pCi ^{32}P minimum detectable activity for the HT-1000, a 3.65×10^{-8} rad cm^2 n^{-1}. fluence to dose conversion factor for fast neutrons (conservative assumption based upon neutron energy of 1 MeV), and the fast neutron portion of the spectrum representing 80% of the dose. The simplified version of the formula is:

$$\text{Dose (rad)} = 6.7\ A$$

Clothing buttons, belt buckles, jewelry and coins can be collected and analyzed for photon emitting activation products. Silver, gold and copper all have (n,γ) reactions for thermal and intermediate neutron energies. Because the neutron flux rate and the spectral energy (critical data for dose equivalent determination) are unknown, induced activity measurements provide extremely valuable information. Large errors (an order of magnitude or more) in the dose evaluation process are to be expected in the absence of data regarding the neutron fluence and spectrum.

Additionally, a rapid determination can be made using a Geiger-Mueller (G-M) detector[3] Clothing and jewelry should be removed and clean clothes should be donned. A G-M detector should be placed against the subject's abdomen and the subject should bend over to envelope the G-M tube for the measurement. If the individual is unconscious or unable to bend over, the G-M tube can be placed in the arm pit. Any induced activity is indicative of neutron exposure.

Experimental exposure of a human torso phantom to 4 rad of fast neutrons indicated the following activity from the ^{24}Na isotope ($^{23}Na(n,\gamma)^{24}Na$ with Na body content based on the value established for standard man)[4]:

Weight of subject lb.	Count rate following exposure cpm	Count rate after 15 hr. c p m
150	275	135
175	310	155
200	350	175
225	400	200

A conversion from cpm to mR/hr is made using approximately 2.8×10^{-4} mR hr^{-1} cpm^{-1}. A general relationship between dose, instrument reading in mR/hr and body weight is

Fast Neutron Dose (rad) = (8000 x mR/hr) / (body weight in lbs.)

This method has a minimum sensitivity of approximately 5 rad immediately for a 175 lb. man with a G-M exposure rate device which has a minimum sensitivity of 0.1 mR/hr after exposure.

2) Radiation Exposure: direct exposure to electron beam

Except for medical therapy there is no reason to construct a facility in which personnel could be exposed to the electron beam directly. CEBAF is no exception. In addition to machine and personnel safety systems the loss of beam from the vacuum containment is inherently self limiting. Duration would likely be limited to less than 100 microseconds. Direct beam exposure is given consideration here only for comparison purposes.

The energy deposited in tissue (water for our purposes) from an electron beam is a function of the mass stopping power of the interaction medium and fluence of electrons. The absorbed dose in rad for a monochromatic beam of electrons is approximated by:

$$1.602 \times 10^{-8} \Phi(S/\rho) \text{ col}, \infty \text{ approx.}$$ [5]

The *minimum* hazard can be indicated by choosing the minimum stopping power value of 1.829 MeVcm^2 g^{-1} (at 1.5 MeV) for tissue. The energy deposition for a 200 μA electron beam with a cross-section of 1 cm^2 is approximately 3.6 erg g^{-1} sec^{-1}. This results in a dose rate of approximately 1×10^{11} rad hr^{-1} to the tissue involved. It is clear that a millimeter beam spot at 200 microAmp will deposit a substantial amount of energy - approximately 86 cal g^{-1} sec^{-1}. This will result in a increase over body temperature to boiling in less than 1 second. The overriding concern may well be thermal tissue damage and the associated morbidity depending on the area irradiated. An average human being represents approximately 1 radiation length of water. If one assumes a neutron production source term of approx. 10^{12} sec^{-1} for the 400 MeV, 200 μA beam, the dose rate at one cemtimeter can be approximated by

$$H \cong 1.2x10^{-4} YP / 4\pi d^2$$ [6]

where Y is the yield in neutrons per second, P is the power in kWatts, and d is the distance. The corresponding neutron dose (corrected for thin target situation) is approximately 10^7 rem hr^{-1}, four orders of magnitude lower than the minimum dose due to direct beam exposure. The distribution of the dose and the impact on the whole body or associated organ system is critical, and, in keeping with attempting to establish a *minimum* hazard no account for this is included in this approximation.

Notes: 1 A calculation using the model proposed by Jenkins in Nuclear Instruments and Methods. See attachment 1.

2. IAEA 152 Evaluation of Radiation Emergencies and Accidents, page 32.

3. IAEA 152 Evaluation of Radiation Emergencies and Accidents, page 34.

4. ICRP Publication 26, 1977

5. IAEA 188, Radiological Safety Aspects of the Operation of Electron Linear Accelerators, page 43.

6. IAEA 188, Radiological Safety Aspects of the Operation of Electron Linear Accelerators, page 82.

Thanks are due Scott Schwahn for checking the figures, Jim Boyce and Ron Sundelin for their review.

Draft Procedure for RCG Staff

1) Shut down beam producing operations.

2) Ascertain the position of person relative to highest potential radiation source. If the person is found near the source leave all clothing buttons, belt buckles, coins and jewelry at the location of the person. Measure the distance between the individuals location and the expected source of radiation.

3) If the position of the person with respect to the source is unknown or the person is not found near the source, collect jewelry, buttons, and biological samples (as appropriate) for analytical measurements and ascertain as much as possible, by questioning the person, their location with respect to possible radiation sources.

4) Perform the rapid determination quick sort method to determine if activation due to neutron exposure has occurred.

5) Contact the CEBAF Medical Services Physician. Make immediate arrangements for hospitalization, medical records transfer and ensure a CBC with differential is taken within four to six hours. A Health Physicist will remain with the exposed individual and be available to assist the physician in treatment if necessary.

6) Arrangements should be made for transfer to REACTs facility in Oak Ridge with in 12 hours if initial resluts indicate that it may be necessary.

7) Additional RCG staff should recreate the event and make the appropriate measurements for neutron spectral quality, fluence, and distribution. Both dose and dose equivalent approximations should be calculated and reported to the Health Physicist at the medical facility with the exposed individual.

Attachment 1, Calculation for High Power Beam Dump
Nuc. Instr. and Methods, 1979, Vol 159, pg.265
"Jenkins" method of Neutron & Photon Shielding
Spreadsheet calculates Neutron & Photon D.E. through a shield and ground water activity from high energy neutron spallation

Dump Z	29	(copper)
Beam Energy	0.4	GeV
Beam Current	200	microA
	or 1.24829E+15	e-/sec
Angle off beam axis	90	degree(s)
Power	80	kW

Neutron Yield Angular Production Terms For Cu/Fe Combination			Fe only
Angle off beam axis	90	degree(s)	
H.E. term	2.130E-04	n/sr*GeV*e-	1.50E-04
M.E. term	4.445E-03	n/sr*GeV*e-	3.13E-03
G.R.N. (isotropic)	0.069630065	n/GeV*e-	

Bremms Yield Angular Production Term		
Angle off beam axis	90	degrees
Term	0.83	phot/sr*GeV*e-
Buildup	1	unitless

Src to POI	1.5	meters
Angle off shield normal	90	degrees

Shielding Data

Material	Thickness, m		Percent void	Actual Thickness, m
Concrete	0	tunnel wall	0	0
Dirt	0	15 ft.	0	0
Iron	1.265		1	1.25235
Lead	0		0	0
Water	0		0	0

Shielded Dose Equiv. Data	mrem/hr	H.E. NeutronSpallation Activating flux	Fluence
High Energy Neutrons	2764.372965	6358.058	1.8E+09
Med Energy Neutrons	5848.491871	13451.53	3.8E+09
G.R. Neutrons	1840.352099	n/a	n/a
Bremms	3.78932E-05	n/a	n/a

Dose Rate at North Access Hatch Due to 45 MeV Dump

The dose rates due to gamma and neutron radiations are calculated at the North Access building drop hatch for a partially shielded dump to estimate potential dose rates in the area. The 45 MeV dump was being used at a current of 200 μA continuous wave (CW), with 6 inches of lead shielding surrounding the dump, but without the recommended water shielding.

Gamma Component

The gamma source term may be approximated by the following formula:

$$H_0 = BTS_s (60\ \mathrm{min}/hr)(0.2mA)/(1m^2) \tag{1}$$

where BT is the product of the buildup factor and the transmission (uncollided flux) of the gamma through the lead shielding (NCRP,106); S_s is the sideward production of bremsstrahlung in (rad-m^2/mA-min)(NCRP,95).

The scattering in the "labyrinth" of the tunnel may be estimated with the following formula (Sch,423):

$$H = H_0 \times B(E_0, L, R) \ln[1+(\pi L^2)^{-1}] \tag{2}$$

where H is the dose rate at the wall of the first duct; H_0 is the source term. $B(E_0,L,R)$ is the buildup factor due to the initial energy E_0, duct length L, and duct lateral dimension R. This value typically ranges from 1.0 to 1.5, so **1.5** was chosen as the more conservative value.

Equation (2) may be employed with the source term from Equation (1), and L being **25** meters. Equation (2) may be reapplied with the previous result used as the source term and L being 36 meters. The scattering coefficient down the second leg of a labyrinth may be estimated as **0.02**, with the given length of **36** meters and the cross-sectional area of 9 m^2 (Sch,421). A shielding coefficient for the thickness of the drop hatch is also used, from $e^{-\mu x}$ = **0.44**.

So, for an example problem of 25 MeV, 200 μA beam, the gamma source term for the dump is:

$$H_0 = (9.1E-4)(2.5E+3\,rad\,m^2 mA^{-1} \mathrm{min}^{-1})(60\mathrm{min}/hr)(0.2mA)/(1m^2)$$
$$= 27\,rad/hr$$

The dose rate at the wall at the end of the first leg of the labyrinth is:

$$H_1 = (27\, rad/hr)\,(1.5)\ln[1+(\pi(25)^2)^{-1}]$$
$$= 21\, mrad/hr$$

The dose rate at the top of the drop hatch is:

$$H_2 = (21\, mrad/hr)\,(1.5)\ln[1+(\pi(36)^2)^{-1}]\,(0.02)\,(0.44)$$
$$= 0.067\, mrad/hr$$

Neutron Component

The neutron fluence at 100 cm from the dump may be approximated from the following formula:

$$\phi_0 = \frac{Y(n\ s^{-1} kW^{-1} copper)\, E(MeV)\, I(mA)}{4\pi\,(100cm)^2} \qquad (3)$$

where Y is the neutron yield from an infinitely thick target due to an electron beam of a given energy.

The dose rate, from rule-of-thumb approximation, may be determined from (IAEA,65):

$$\dot{H}_0(rem/hr) \approx 1.2E\text{-}4\ \phi(n\ cm^{-2} s^{-1}) \qquad (4)$$

The transmission through lead is taken from an approximate 15 cm thickness and an average attenuation length of 391 g/cm^2, and is **0.65**. Using universal transmission curves (and knowing the length and cross-sectional area of the labyrinth)(Sch,420-421), the scattering terms are:

scatter down first leg from dump	**0.02**
scatter from first leg to second	**0.0001**
scatter from second leg to hatch	**0.06**.

So, for an example problem of 25 MeV, 200 μA beam, the neutron source term for the dump is:

$$\phi_0 = \frac{(3.5E11 n\sec^{-1} kW^{-1})\,(25MeV)\,(0.200mA)}{4\pi\,(100cm)^2}$$
$$= 1.4E7\ n\ cm^{-2} s^{-1}$$

The dose rate at the dump is:

$$\dot{H}_0(rem/hr) = (1.2E\text{-}4)\ (1.4E7) \\ = 1.7E3\, rem/hr$$

The dose rate at the drop hatch after multiple scatterings is:

$$\dot{H}_s = (1.7E3\, rem/hr)\ (0.65)\ (0.02)\ (0.0001)\ (0.06)\ (1E6\, \mu rem/rem) \\ = 130\, \mu rem/hr$$

Evaluation

The results of the above calculations are plotted for electron energies up to 50 MeV, at a current of 200 μA. Empirical measurements were taken at the drop hatch under the conditions of 200 μA and 28 MeV and 42 MeV. The resultant dose rates were **240 μrem/hr** neutron and **35 μrem/hr** gamma at 28 MeV, and **50 μrem/hr** gamma at 42 MeV (neutron measurements at 42 MeV were not made). These empirical results closely match the calculated results, with the calculated gamma erring on the conservative side. Below about 20 MeV, neutron production rapidly falls off, and the gamma dose rate begins to dictate the posting requirements.

Adding approximately **20 inches** of water would considerably reduce the dose rate at the drop hatch. The attenuation length for neutrons that are assumed to be equivalent to the fission spectrum is **9.5 g/cm²** (IAEA,195). Therefore, the attenuation of the neutrons is estimated to be:

$$\dot{H} = \dot{H}_0 e^{-[\mu(cm^2/g)\,\rho(gm/cm^3)\,x(cm)]} \\ = \dot{H}_0 e^{-[(0.105)(1.0)(50.8)]} \\ = 4.8E\text{-}3\ \dot{H}_0$$

The mass attenuation coefficient for photons in water may be estimated with its average atomic number Z (7.1). The Z of nitrogen is 7, so the mass attenuation coefficients for nitrogen may be used as a close approximation. The mass attenuation coefficient is, for the most part, unchanging in the energy range of 10 MeV to 50 MeV, at 0.017 cm^2/g (Chi,429). This figure is equivalent to a tenth-value layer (TVL) of 136 g/cm^2, which closely matches that of concrete, as found in IAEA 188 (p.174).

The properties of concrete and water at these energies are known to be very similar. The photon transmission for the water, then is approximately:

$$\dot{H} = \dot{H}_0 e^{-[\mu/\rho(cm^2/g)\,\rho(g/cm^3)\,x(cm)]} \\ = \dot{H}_0 e^{-[(0.017)(1)(50.8)]} \\ = 0.42\ \dot{H}_0$$

Conclusion

The estimated photon dose rate at the North Access Building drop hatch is the only radiation of concern during 200 μA beam operations to the 45 MeV dump, assuming 20 nominal inches of water and 6 nominal inches of lead shielding. The second graph illustrates the calculated estimates of dose rates from fully shielded dumps. In all conditions, calculated dose equivalent rates remain below 50μrem/hr, which is the limit above which Controlled Area postings must occur. If unrestricted operations are required, both the water and lead shielding are required.

References

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Schopper, H., Shielding Against High Energy Radiation, Group 1, Volume 11 of **Numerical Data and Functional Relationships in Science and Technology**, Springer-Verlag, New York, 1990.