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UCID-20881

Dosimetry Measurements of X-Ray and Neutron Radiation Levels Near the Shuttle and End Beam Dump at the Advanced Test Accelerator

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Work performed jointly under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48 and for the Department of Defense under Defense Advanced Research Projects Agency DARPA Order No. 4395, monitored by Naval Surface Weapons Center under document number N60921-85-POW0001; and Naval Surface Weapons Center under document number N60921-85-WRW0201.

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5205 Port Royal Road
Springfield, VA 22161

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DOSIMETRY MEASUREMENTS OF X-RAY AND NEUTRON
RADIATION LEVELS NEAR THE SHUTTLE AND END BEAM DUMP AT THE
ADVANCED TEST ACCELERATOR

1. INTRODUCTION

Electron beams as a source of directed energy are under study at the Lawrence Livermore National Laboratory (LLNL). An intense 10-kA, 50-MeV, 50-ns full-width half-maximum, pulsed electron beam is generated by the prototype Advanced Test Accelerator (ATA) at the Laboratory's Site 300. The ATA is being used to conduct precursor experiments that ultimately will lead to the crucial test of electron beam propagation in the atmosphere. Whenever the electron beam is stopped in materials, intense radiation is generated. Estimates based on available data in the literature¹ show that for materials such as lead, photon radiation (x ray, gamma, bremsstrahlung) levels can be as large as 10^4 roentgens per pulse at 1 m in the zero-degree direction (i.e., the electron-beam direction). Neutrons, which are emitted isotropically, are produced at a level of 10^{13} n/m² per pulse.² Depending upon the number of pulses and the shielding geometry, the accumulated dose is potentially lethal to personnel and potentially damaging to instrumentation that may be used for diagnostics.

To provide shielding for minimizing the risk of exposure to personnel and radiation damage to instrumentation, it is important to determine the x-ray and neutron radiation environment near beamline components such as the beam shuttle dump and beam stop. Photon and neutron dosimetry measurements were performed around the beam shuttle dump on January 9, 1985, and near the carbon beam stop at the end of the beamline before the entrance to the diagnostic tunnel on April 12 and December 23, 1985. These measurements together with simple rule-of-thumb estimates and Monte Carlo electron-photon shower calculations of the absorbed dose are presented in this report.

2. Experimental Procedure

An intense source of x-ray and neutron radiation in the ATA beam-handling system is the beam shuttle dump, which is used to stop the beam during beam-diagnostics studies. A schematic cross-sectional view looking upstream in the shuttle dump is shown in Figure 1. The electron beam is actually stopped in a series of water-cooled carbon plates having small apertures.

Figure 1. A schematic cross-sectional side view of the beam shuttle dump working upstream.

Electron-photon transport calculations have been made to determine the amount of energy deposited in these carbon plates inside the dump by the ATA electron beam.³

The dosimetry measurements were performed outside the shuttle dump with the assistance of personnel from LLNL's Hazards Control Department who placed dosimeters 1 m apart along strings, which were attached at one end to the top of the center of the beam shuttle dump and at the other end to the tunnel wall. Seven strings were attached between the dump and various locations along the wall defining angular positions of 24°, 30°, 45°, 60°, 90°, 120°, 135°, 150°, and 165° as shown in Figure 2. Small wax-paper envelopes were attached by safety clips to 30 known positions along the strings. Three LiF thermoluminescent chips⁴ sensitive to x-ray radiation were placed in each of the 30 envelopes, and three CR39 plastic wafers⁵ sensitive to fast neutrons were placed in envelopes at selected positions. One thermoluminescent chip and one CR39 plastic wafer, of the three exposed at each position, were used to set the reading process on the proper scale. Thus, two x-ray and two neutron readings were available for each measurement location. A photograph

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Figure 2. A schematic of the geometry of the surveyed dosimeter positions showing angles and distances relative to the center of the shuttle dump and electron beam direction.

of the matrix of dosimeters suspended from the strings around the shuttle dump is shown in Figure 3.

The first set of measurements was taken on the beam shuttle dump January 9, 1985. The accelerator operator delivered approximately 5 kA of current at a beam energy of 37 MeV into the shuttle dump. Approximately 0.037 kA of current was transmitted through the shuttle and was eventually stopped in carbon in the beamline beyond the shuttle dump. After the accelerator was properly tuned and stabilized, the pulsed power to the injector and accelerator was switched off. The experimenters then entered the target area and placed the dosimeters in the envelopes at the previously surveyed locations marked along the string. After returning to the control room, the pulsed power was switched on and a counter recorded the number of electron pulses. After approximately 11 min, 758 pulses were recorded and the pulsed power was again switched off. The total charge deposited in the shuttle dump by the electrons was determined from $Q = 758 \text{ pulses} \times 50 \times 10^{-9} \text{ s/pulse} \times 5 \times 10^3 \text{ C/s}$ and is equal to 0.19 C. The experimenters, together with personnel from Hazards Control, entered the target area to retrieve the dosimeters, which were then stored for future readout. Similar exposure and recovery procedures were followed on April 12 and on December 23, 1985, except that the dosimeters were placed around the beam stop at the end of the propagation tank. Accumulated charge was more carefully determined by integrating the beam current monitor signal from the dump area and summing over all the shots. A schematic of the beam stop for the second set of measurements is shown in Figure 4.

Figure 3. A photograph of the shuttle dump and dosimeters suspended in position.

Figure 4. A schematic of the cross-sectional side view of the beam stop.

3. Calibration of the Dosimeters

The x-ray thermoluminescent dosimeters (TLD) were read out by LLNL's Hazards Control Department. The TLDs consist of three LiF crystals in a plastic holder about 4 cm in diameter. Radiation elevates the LiF crystal into trapped higher energy states. When heated by hot, dry nitrogen, the LiF crystals return to the ground state and emit visible light. Using a photo-electron multiplier tube and suitable electronics, the roentgen dose to the LiF crystal can be determined. The system is calibrated by exposing the dosimeters to radioactive sources ^{60}Co and ^{137}Cs of known intensity. Each position had two dosimeters; hence we record in Table 1 the average value in units of roentgens together with position number, angle, and distance, and the tabulated error is taken as the standard deviation of the mean value.

The neutron plastic wafers, which were supplied by Hazards Control, were calibrated using a ^{252}Cf spontaneous fission source. It was known that the

Table 1. January 9, 1985, exposure ($Q = 0.19$ C).

Position	Angle (deg)	Distance (meters)	Dose (roentgens)	Neutron fluence (n/cm ²)
1	24	3	1476 $\pm$ 204	3.1 x 10 ⁸ $\pm$ 5%
2	24	5	469 $\pm$ 28	1.8
3 ^{a,b}	24	6	360 $\pm$ 36	1.6
4 ^{a,b}	30	3	16.7 $\pm$ 10.3	3.2
5	30	4	867 $\pm$ 130	2.5
6	30	5	495 $\pm$ 18	2.0
7	45	3	1218 $\pm$ 183	3.5
8	60	3	830 $\pm$ 14	3.9
9	90	3	235 $\pm$ 5	3.4
10	120	3	139 $\pm$ 10	2.0
11	135	3	125 $\pm$ 10	1.7
12	150	2	98 $\pm$ 4	1.8
13	150	3	98 $\pm$ 4	1.8
14	150	5	56 $\pm$ 1	1.3
15	165	1	1294 $\pm$ 225	2.7
16	165	3	126 $\pm$ 7	0.9
17	165	5	39 $\pm$ 4	0.7
18 ^a	165	9	6.6 $\pm$ 0.5	0.4
19	24	4	836 $\pm$ 11	---
20	45	2	3169 $\pm$ 44	---
21	45	4	671 $\pm$ 20	---
22	60	2	1706 $\pm$ 563	---
23	90	2	426 $\pm$ 9	---
24	120	1	329 $\pm$ 9	---
25	120	2	239 $\pm$ 13	---
26	135	1	157 $\pm$ 9	---
27	135	2	211 $\pm$ 21	---
28	150	1	943 $\pm$ 66	---
29 ^b	165	2	69.7 $\pm$ 48	---
30 ^a	165	7	9.3 $\pm$ 0.05	---

^aLine-of-sight is partially obstructed.

^bOne defective TLD.

source produced 2.51×10^3 n/s. Therefore, at 1 m from the source, the neutron fluence was 1.997×10^3 n/s-cm² assuming isotropy. The plastic wafers were exposed at 1 m for 2.68 h, and 706 tracks/cm² were recorded corresponding to a calibration factor of $1 \text{ n/cm}^2 = \text{tracks/cm}^2 / 3.66 \times 10^{-5}$. The final neutron fluence results are tabulated in Table 1.

On April 12 and December 23, 1985, a similar set of x-ray radiation and neutron dosimetry measurements were made in the diagnostics tunnel. In this case, the beam passed through the shuttle and stopped in the water-cooled carbon beam dump at the end of the beamline. Approximately 0.21 C of electrons having an energy of 39 ± 1 MeV were delivered to the end beam dump. The results of the dosimetry measurements are tabulated in Table 2. Measurements taken on December 23 at $E_0 = 42 \pm 1$ MeV are shown in Table 3.

4. Discussion of Results

The shuttle dump is a complex distributed source of radiation. It is a large rectangular aluminum box in which the electron beam loses energy by passing through a series of carbon plates over a distance of about 1 m. The carbon is surrounded by water-cooled plates and other materials that present different shielding thicknesses to the radiation. In addition, dosimeters at 24° and 165° and perhaps at 30° were partially obstructed by support materials surrounding quadrupole magnets. Since there is no simple geometrical symmetry in the shielding or radiation source, interpretation of the final dosimetry results by comparison with calculations is difficult.

Although the radiation source is not a simple point source, we have, for purposes of conveniently comparing the dose at different distances, normalized all doses to 1 m by assuming the dose decreases with distance as r^{-2} . Therefore, the x-ray dose tabulated in Table 1 is divided by the total charge ($Q = 0.19$ C) and multiplied by r^2 and plotted in units of R-m²/C in Figure 5. Different symbols are used to characterize the dose measured at various distances. Examination of the plot shows that for angles less than or equal to 90°, the normalized doses at particular angles are consistent with each other, indicating that at forward angles the absorbed dose is decreasing as r^{-2} over distances of at least 2 to 4 m. Beyond 90° there is greater scatter in the data, reflecting the fact that the point-source approximation is simply invalid. To find a better fit to the radial dependence of the dose

Table 2. April 12, 1985, exposure (Q = 0.21 C).

TLD	Angle (deg)	Distance from center (meters)	Dose (roentgens)	Neutron fluence (n/cm ²)
81569	0	3.0	2.03×10^4	Saturated
63	0	18.0	3830	$1.40 \times 10^8 \pm 5\%$
61	0	33.0	2660	0.70
60	0	40.5	1030	0.39
59	0	48.0	155	0.27
58	0	55.5	121	0.24
57	0	63.0	93	0.20
56	0	70.5	68	0.17
55	0	78.0	52	0.18
65	30.0	33.0	63	8.99
66	30.0	25.5	161	0.15
	30.0	18.0	390	0.35
68	30.0	10.5	353	1.04
70	18.3	3.0	524	1.60
71	44.7	3.0	882	1.44
72	71.7	3.0	2109	1.67
73	75.0	3.0	1280	1.46
74	90.0	3.0	4708	1.67
75	102.9	3.0	2740	1.57
76	124.7	3.0	2319	1.47
77	132.5	3.0	1793	1.46
78	143.6	3.0	1720	1.37
79	168.3	3.0	2319	1.38

Table 3. December 23, 1985, exposure ($Q = 0.0028$ C).

TLD	Angle (deg)	Distance from center (meters)	Dose (roentgens)
850240	0	5	172.3 ± 7.2
41	0	8	83.9 ± 2.7
42	0	11.1	46.1 ± 1.0
43	0	14.1	40.8 ± 2.4
44	0	17.2	30.9 ± 1.2
45	0	20.2	34.8 ± 1.7

at back angles and reduce this scatter, the dose in R/C is plotted versus the log of the distance and compared to assumed r^{-1} , r^{-2} , and r^{-3} radial dependence, as shown in Figure 6. It appears that r^{-2} fits better at smaller distances and r^{-3} at greater distances. One would not expect this, since the shuttle represents a radiation source somewhere between a point source and a line source. Thus, some combination of r^{-1} and r^{-2} should fit the data. It is possible that the dosimeters farthest from the source at 165° may be partially shielded from the primary radiation source by the support structure of the entrance quadrupole, resulting in lower readings.

Results from a Monte Carlo electron-photon shower calculation using the computer code SANDYL⁷ is given by the solid line in Figure 5. The calculation was performed in three-dimensional geometry, and the important components of the shuttle dump were modeled using combinational geometry. The energy deposited in LiF dosimeters at a fixed distance of 1 m from the center of the shuttle dump between 0° and 90° was calculated by following 10,000 electrons down to a cutoff energy of 10 keV. The agreement between the calculation and data at 30° is probably fortuitous: components of the support structure of the beamline obscure the direct line-of-sight between the center of the shuttle and the dosimeters at 24° and 30° , and this factor was not included in the calculation. One possible explanation of why the calculation undershoots the data at 45° and 60° is that we are incorrectly normalizing the data to 1 m by multiplying by r^2 . Another possibility is that there is an

Figure 5. Angular distribution of the x-ray radiation dose multiplied by the square of the distance compared to the calculated dose 1 m from the center of the shuttle dump.

Figure 6. A plot of the measured x-ray radiation dose at $\theta = 165^\circ$ versus the distance between the center of the shuttle dump and dosimeter.

additional source of radiation originating upstream caused by the beam halo or by a mis-steered beam striking the sides of collimators as it passes through them. The dosimeters in the forward direction and closest to the beam tube would intercept more of the forward-scattered radiation caused by the beam spill. More detailed plots illustrating the angular distributions of the x-ray radiation dose for measurements at fixed distances at 2, 3, and 5 m are shown in Figures 7, 8, and 9.

The neutron radiation fluence per coulomb is plotted versus the log of the distance between the dosimeter and the center of the shuttle for fixed angles of 24° , 30° , 150° , and 165° in Figure 10. The smooth line through the data is an eyeball fit assuming the radiation decreases with distance as r^{-1} . This is consistent with an assumed line source of neutrons and inconsistent with a r^{-2} decrease, which best described the x-ray radiation at forward angles.

The neutron fluence plotted in Figure 10 is multiplied by the distance in m to account for the r^{-1} dependence, and all the data is plotted versus angle in Figure 11. The peak neutron yield is about 6×10^9 n-m/cm²-C at $\theta = 60^\circ$. Using the published neutron yield² for 34-MeV electrons on carbon and assuming isotropy, the deduced yield to be compared with the data in Figure 11 is 1.3×10^{10} n-m/cm²-C, which is about twice as high. Absorption of neutrons by the carbon and shuttle dump walls has not been included in this estimate.

In Figures 12, 13, and 14, the x-ray and neutron dose measurements made on April 12, 1985, are plotted. Additional measurements made on December 23, 1985, are plotted as triangles in Figure 12. Between 50 and 90 m, the x-ray dose decreases with distance as r^{-2} , as might be expected far from the source of the radiation. Again using Ref. 1, the x-ray dose at 0° from a 39- to 42-MeV electron beam incident on a high-Z target optimized for emission rate is 9×10^5 rads-m²(mA)⁻¹ min⁻¹ or 1.51×10^7 R-m²/C. For low-Z material ($Z = 6$) assuming a $Z^{1/2}$ dependence,⁶ the yield is reduced by a factor of 0.34. Since the carbon beam stop is about 30 cm long and the electron range is about 11 cm, the emitted x-ray yield will be attenuated at least by the remaining 19 cm at 0° . Assuming exponential attenuation with $\mu = 0.05$ cm²/gm for a 1-MeV photon, we get a reduction factor of 0.10. The expected dose 1 m from the carbon beam stop at 0° becomes 5.2×10^5

Figure 7. Angular distribution of the x-ray radiation dose measured 2 m from the center of the shuttle dump.

Figure 8. Angular distribution of the x-ray radiation dose measured 3 m from the center of the shuttle dump.

Figure 9. Angular distribution of the x-ray radiation dose measured 5 m from the center of the shuttle dump.

Figure 10. A plot of the neutron fluence versus distance for selected angles.

Figure 11. Angular distributions of the neutron fluence multiplied by the distance from the center of the shuttle dump. (The curve through the data is to guide the eye.)

Figure 12. A plot of the x-ray radiation dose at $\theta = 0^\circ$ versus distance measured from the center of the end beam dump.

Figure 13. A plot of the neutron fluence at $\theta = 0^\circ$ versus distance measured from the center of the end beam dump.

Figure 14. Angular distribution of the neutron fluence multiplied by the distance from end beam dump (3 m).

$R\text{-m}^2/C$. Assuming a point source and, therefore, a r^{-2} decrease in dose with distance, the dose is calculated and the result is plotted as a dashed straight line in Figure 12. The measured dose is about 2 to 5 times larger than this crude estimate. Results from a Monte Carlo electron-photon shower calculation using the computer code SANDYL, as described earlier,⁷ are plotted as open circles together with statistical errors in Figure 12. This comparison shows that the calculation and the data are in agreement for distances less than 5 m and greater than 50 m from the center of the carbon beam stop. In between, the measured dose is definitely higher than predicted, and a pronounced bump occurs in the data in the 20- to 40-m range. The dose measurements were made on two occasions and are roughly consistent. The origin of this radiation enhancement is not known. One interesting possibility is that photon radiation reflected from the walls of the diagnostic tunnel could produce this effect.

It is also interesting to note that the neutron dose at 0° decreases with distance as r^{-1} to a distance of about 30 m and not as r^{-2} as shown in Figure 13. Near 40 m an abrupt decrease in dose takes place, and then beyond 50 m the dose again decreases as r^{-1} . The angular distribution of neutron dose at 3 m is isotropic as expected and is shown in Figure 14. Realistic neutron calculations were not performed.

5. Radiation Damage

Threshold levels for damage to electronic components such as transistors and resistors resulting from x-ray radiation is typically 10^3 rads.⁸ Inspection of Figure 5 shows that at 1 m from the shuttle dump the radiation dose is about 10^4 R/C or 1.9×10^3 R or 1.7×10^3 rads for $Q = 0.19$ C, which corresponds to an exposure of 11 min for a 5-kA pulsed beam whose full width at half maximum is 50 ns. At forward angles, the dose levels are an order of magnitude larger. It is clear, therefore, that x-ray radiation levels are sufficient to cause damage to unshielded instrumentation near the beam dump in a relatively short time. Damage in this case can be considered to have occurred when, for example, the current gain of the transistor begins to change as a result of exposure to radiation. (For more details see Ref. 8.)

Threshold levels for damage to electronics by neutrons are typically 10^{12} n/cm². From Figure 10, the peak neutron fluence levels at 1 m at

an angle of 60° are 6×10^9 n/cm²/C. For our exposure of 11 min, this corresponds to 1.1×10^9 n/cm². Since this level is 10^3 lower than the threshold value, neutrons are not expected to be a source of radiation damage over short times. Such effects, however, will be cumulative.

6. Conclusions and Future Studies

The x-ray dosimetry measurements near the shuttle dump yield dose levels about a factor of 2 higher than that predicted by Monte Carlo calculations in the angular range 45° to 90° . The disagreement between the data and the Monte Carlo calculation probably arises because the calculations were performed to yield the dose at 1 m, and the data taken at 2 to 4 m were incorrectly normalized to 1 m assuming r^{-2} fall-off. Estimates from published neutron fluence data are too high by a factor of 2. Neutron Monte Carlo calculations were not performed. Further discrepancies between experiment and predictions have also been found for the 0° x-ray data taken at the beam stop (end dump) farther downstream. Dose levels were found to be larger by factors of 2 to 5 at distances of 5 to 40 m into the diagnostic tunnel. The effects of the walls of the tunnel were not included in the calculations and should be investigated further.

We emphasize that the comparison of the data with electron-photon-shower Monte Carlo calculations is not intended to be a "benchmark" test of the shower code. In fact, because the shuttle dump and beam stop have complex geometries and are in complex environments that are very difficult to model in a transport code, we performed the measurements to get a more reliable determination of the x-ray and neutron radiation yields than we would expect from calculations.

On the other hand, there have been benchmark experiments to test Monte Carlo calculations in simple slabs of solid materials⁹ ($E_0 = 500$ MeV) and liquids¹⁰ ($E_0 = 100$ MeV). Generally, good agreement ($\leq 10\%$) is found between the forward angle off-axis dose measurements and the transport calculations.

For experiments now in the planning stage at the ATA that require the beam in open air, good predictions of the radiation levels are essential because it is not possible to shield against all radiation emanating from the entire length of a diffused beam as it loses energy in the open air.

Calculations of the spatial energy deposition in air by electron beams of energy 0.05, 0.5, 1.0, and 10.0 GeV have been performed by several authors.¹¹⁻¹³ None of these calculations has been checked against experiment. In open air it will be particularly important to estimate the level of backscattered radiation or what is commonly known as "sky shine." Results from electron-photon shower codes such as SANDYL are not expected to be too reliable in the backward direction and have not been tested against experiment in these geometries. At back angles, nuclear reactions such (γ, n) and inelastic nuclear electron scattering become increasingly important because the coulomb cross reactions become successively weaker with increasing angle. Neutron production, electron induced fission, etc. and subsequent gamma radiation are not included in the state-of-the-art electron-photon shower codes.

To study further and to provide a rigorous test of transport calculations including backward scattering geometries, new benchmark experiments have been proposed and are underway at various facilities.¹⁴⁻¹⁷

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