DTL Tank Shielding Needs in the SNS Front-End Building

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1. Introduction

In view of determining what type and amount of shielding will be needed to protect workers in the SNS Front End (FE) building from radiation coming from the first two SNS DTL tanks, the evaluation of x-rays coming from the 4 DTL tanks of the LANSCE linac with the RF on, but without beam has been measured. A total of 60 thermo-luminescent dosimeters (TLDs) provided by LANL were exposed as well as 46 TLDs and two Siemens electronic personal dosimeters (EPDs) belonging to ORNL. Measurements were made during a 2 hour period of normal RF operating conditions for tanks 1 and 2, and a 1 hour period for tanks 3 and 4 (see fig.1 and tables 1 and 2). TLDs were placed on the surfaces of the tanks at half height, at the high and low energy end plates of the tanks 1 and 2, at penetrations on the top, side, and bottom surfaces of tanks 1 and 2 and along the tunnel wall. A set of measurements was also made with TLDs shielded by varying amounts of lead in order to obtain some information about the x-ray energy spectrum (see fig.2).

A detailed description of the TLD exposure results is presented, followed by an interpretation section and a discussion on scaling intended to predict the corresponding x-ray levels expected in the FE building. Finally, preliminary recommendations are made for shielding in the SNS FE building.

2. Exposure Results for LANSCE DTL tanks 1 and 2

Two LANL TLDs and one ORNL TLD were dedicated to Background measurements (see table 1.). These TLDs were not exposed in the experiment, but accompanied the experimental TLDs at all other times. All these units showed zero exposure, as expected. Neutron exposures were reported on two LANL TLDs, but neighboring TLDs did not indicate neutron exposures and there is no predicted source of neutrons – these results are thought to be spurious.

Four LANL TLDs were exposed during conditioning of the tanks following the maintenance period. However, the tanks were not opened during this maintenance period, and conditioning was uneventful – there were no sparks, and conditioning was completed in about five minutes. The two TLDs placed on seams at each end of tank 2 were intended to estimate the radiation exposure of gaskets during conditioning – no exposure above background was detected during this limited test. The other two TLDs were placed opposite the RF inlet on tank 2 and on the beam line at the exit of tank 2. These TLDs recorded exposure rates comparable to (but somewhat larger than) the corresponding values during normal operation. We suspect that either we have underestimated the RF-on time during this test or the changing conditions during the power-up/power-down cycles create unstable exposure conditions.

TLDs were placed toward the outer edges of the tank end-faces at the low-energy end of tank 1 and at the high-energy end of tank 2 at 90 degree intervals (top, tunnel-side, bottom, wall-side). At each end, there was significant angular variation in the dose rate (up to factors of seven and ten difference between positions). In each case, the bottom exposure was lowest. At the low-energy end of tank 1, the top dose rate was 50% higher than each of the two side values, while at the high-energy end the tunnel-side dose rate was highest, followed in order by the top, wall-side, and bottom. Additional TLDs at the high-energy end of tank 2 were placed on the beam line and halfway between the beam line and the outer edge of the tank. The measured dose rates at these positions were intermediate between outer-edge values.

Eight TLDs were placed on the tank 2 surface next to drift-tube penetrations on top of the tank. Four additional TLDs were placed on the tank 2 surface next to post-coupler penetrations. It was surmised that x-ray levels might be higher next to penetrations compared to levels measured through the tank surface. We did not observe that any of the penetrations had obvious thin points that might provide reduced shielding. In fact, dose rates at the top penetrations tracked the corresponding measurements on the tunnel-side tank surface, but were about a factor of two (or more) lower – this ratio is consistent with the angular dependence observed at the high-energy tank end face. Dose rates at the penetrations on the side of the tank body were fairly consistent with values found at nearby positions on the tank wall. One TLD placed near an ion pump penetration on the bottom of the tank agreed with a TLD on the sidewall of the tank at the same location.

TLDs were placed at three-foot intervals along the lengths of tank 1 and tank 2 at half height (see fig.1.). Previous measurements of this type have relied on one measurement per tank, and an important objective of this measurement was to have sufficient resolution to determine whether the dark radiation is relatively uniform or varies along the length of a particular tank. The two lowest readings along these tanks were at the seams at the low-energy end of tank 1 and at the tank 1 – tank 2 interface. X-ray levels along the body of tank 1 increased from 95 mrem/h at the low-energy end to 1.3 rem/h at the high-energy end. Tank 2 measurements show a broad maximum (peaking at about 7.5 rem/h) along the first half of the tank, followed by a lower-dose-rate region (averaging about 1.7 rem/h) along the second half of the tank, with a sudden increase in dose rate at the end of tank 2.

LANL and ORNL TLDs placed on the bottom of tank 2 near the RF inlet (near drift tube 37) registered 3.9 and 2.8 rem/h, respectively. A Siemens EPD was also positioned near those TLDs, and it registered 2.6 rem/h.

Measurements were also made on the tunnel wall opposite the RF inlet, about seventeen feet from the surface of tank 2. Dose rates at this location measured to be 350 mrem/h both by a LANL TLD and by a Siemens EPD.

Some idea of the energy spectrum of the x-rays penetrating the tank was obtained by exposing LANL and ORNL TLDs covered by varying thicknesses of lead. Agreement between the two sets of results was excellent (see fig.2). For the two intermediate thicknesses of lead, the TLD deep doses (see appendix) were half of the shallow doses, indicating that the spectrum was relatively “soft” after that shielding. The ORNL TLD with lead shielding indicated a higher deep dose than shallow dose, which is highly unusual. We suspect that the TLD happened to straddle a tank structure interface so that the deep dose was measured through water and the shallow dose was measured through steel. For the TLD exposure at tanks 3 and 4 care was taken to avoid this problem.

3. Exposure Results for LANSCE DTL tanks 3 and 4

Two TLDs were dedicated to Background measurements like for tanks 1 and 2 (see table 2.). These units showed close to zero exposure, as expected.

Six TLDs were placed along the tunnel wall, opposite the middle of the last section of tank 4 giving the highest reading, corresponding to ~1.7 rem/h. It is to be noted that this TLD was at 9 feet from the tank wall.

The remaining 32 TLDs were placed on the walls of tanks 3 and 4 at 4 foot intervals. Note that dose rates for tank 3 are fairly uniform and remain below half the peak rate for tank 2. The peak dose rate for tank 4, however, is double that of the one for tank 2.

4. Interpretation

From the overall profile of the dose rate measurements along the tank side surface, and analysis of the additional measurements, several conclusions are apparent:

1. The radiation is not uniform along the length of the tanks; no simple pattern was found in the measured data. Local effects such as field emission currents, which highly depend on surface quality, contribute to this non-uniformity [1].
2. Penetrations do not correspond to points of higher radiation, at least when measured on the tank surface next to the penetration. There could still be a beam of increased radiation along the penetration axis – this possibility was not explored in these measurements.
3. Radiation levels at the outside surface of the tank are not uniform around the circumference. Variations may be as much as a factor of ten at some locations, and seem to be commonly at least a factor of two.
4. The energy spectrum of the radiation penetrating the side of the tank appears to be complex. The first one-eighth inch of lead reduces the radiation level by a factor of five, but the next three-eighths of an inch of lead reduces the field by less than an additional factor of three.

5. Scaling to the SNS DTL

In this section, initial scaling is made from LANSCE DTL tank 2 to SNS DTL tank 6 as they have similar maximum gap voltages. Subsequent scaling is made to SNS DTL tank 2. Apart from gap voltage, scaling for peak surface field, RF frequency and duty factor, and attenuation due to tank wall thickness are considered.

Using data from SUPERFISH files, fig.3 shows a plot of DTL gap voltages (in the case of SNS, the maximum for each tank) and surface fields as a function of beam energy. For these data points the corresponding measured dose rates are plotted. Gap voltage scales as $E_0\beta\lambda$; the highest gap voltage in the SNS DTL (found in tank 6) corresponds to gap voltages found in the second half of LANSCE DTL tank 2.

From the SUPERFISH files, the SNS DTL tanks have maximum surface fields of the order of 24 MV/m. Scaling from LANSCE DTL tank 2, which is the one with the highest maximum surface field (about 17 MV/m), electron field emission, based on the Fowler-Nordheim law [2], is about a factor 2 higher for the SNS case for identical field enhancement β.

With roughly double the RF frequency for the SNS DTL compared to LANSCE, the tank radius but also the drift tube sizes are approximately half those of LANSCE.

The about 2.7 inch thick wall of the SNS DTL attenuates X-rays produced by 1. MeV electrons about a factor 7 (or more for lower energy electrons) more than the approximately 1 inch thick LANSCE DTL wall [3].

The RF repetition rate at LANSCE was 120 Hz and will be 60 Hz for SNS with pulse lengths of .835 ms and 1.1 ms respectively (a square pulse shape has been assumed).

Then, scaling for the duty factor, electron field emission and tank wall thickness from the highest dose rate at LANSCE DTL tank 2 to the SNS DTL tank 6 yields:
~ 60 Hz/120 Hz * 1.1 ms/0.835 ms * 2 / 7 * 8 rem/h or about 1.5 rem/h.

With a safety margin (which would take into account effects such as the 25 % underestimation of the TLD readings as mentioned in the appendix), this yields dose rates of about 2 rem/h for a (conditioned) tank 6 at the level of the tank wall. During conditioning much higher dose rates are to be expected at full voltage.

The maximum gap voltage for SNS tank 2 is about 0.6 MV. Due to the increased attenuation of X-rays at this lower energy compared to tank 6, the dose rate is reduced by about a factor 2 for tank 2 w.r.t. tank 6 or 1 rem/h.

It is to be noted that each SNS DTL tank has around its circumference 12 slots, which will house cooling channels and make up close to 21 % of the circumference. These slots are about 1.6 inch deep and 1 inch wide, run along the length of the tank, and yield a wall thickness of only 1.1 inch in these areas. Therefore one may expect a factor 11 higher dose rates (about 11 rem/h) for tank 2 near these areas. For tank 2, taking into account the effect of the cooling slots yields 11.*21%+1.*79% or about 3 rem/h as equivalent dose rate coming from the tank wall. ***Inside the tanks, radiation levels of hundreds of rem/h are to be expected.***

At a distance of 50 inches from the tank wall (in the FE building, the approximate distance between the closest building wall running along the SNS DTL and the DTL tank wall), assuming a line source with fall-off proportional to 1/r, the dose rate drops by 11/61. This yields ***for tank 2*** 3 rem/h*11/61 or ***about 0.5 rem/h near the building wall.***

6. Shielding for SNS DTL tanks 1 and 2

In general occupancy areas the ambient dose rate needs to be < 0.25 mrem/h. A 1.5 inch thick lead wall would give a transmission of about 5.E-04 for X-rays from 0.6 MeV electrons (which corresponds to the highest gap voltage in SNS tank 2). The equivalent thickness for concrete is about 20 inches.

Although the dose rate estimates given above highly depend on local surface conditions within the tanks [1] and can be off by as much as one order of magnitude (note the variations in dose rate along the LANSCE DTL tanks), shielding requirements will be dominated by dose rates expected due to beam loss [4].

If initial conditioning of tank 1 and installation work in the tunnel were needed simultaneously, a temporary (movable) lead shield would be required. In a similar way as for tank 2, scaling for the highest gap voltage in tank 1 (0.28 MV), a lead shield of 0.3 inch would be required.

During commissioning of tank 1 with full average beam power, neutron dose rates of about 150 rem/h are to be expected at 1 m from the D-plate beam dump [5]. If access were needed in the linac tunnel at this time, a (temporary) concrete wall of about 2.4 m thickness surrounding the beam dump would be required.

In any case, dose rate measurements ought to be made during conditioning, commissioning and operation to confirm that the installed shielding is sufficient.

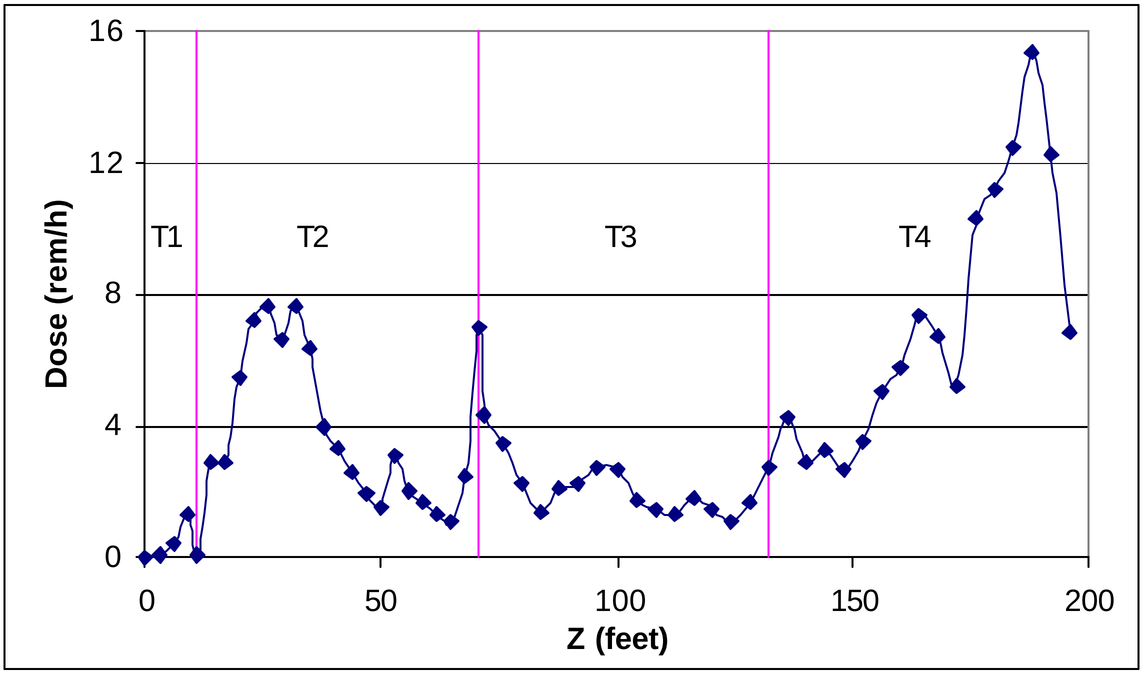

Figure 1.: X-ray dose rates as measured on tanks 1 through 4 of the LANL LANSCE DTL, based on an exposure of TLDs for 2 hours at tanks 1 and 2 and 1 hour at tanks 3 and 4. The TLDs were placed on the tank walls (at half height) along the structure.

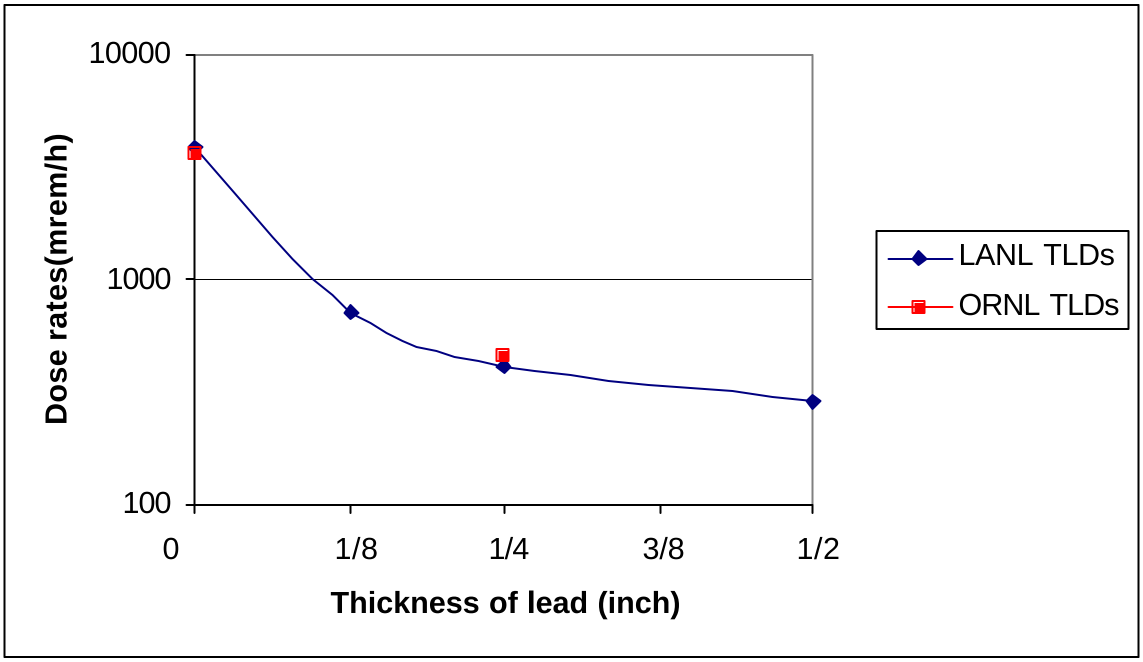

Figure 2.: To get a rough idea of the energy spectrum of the x-rays penetrating the tank, LANL and ORNL TLDs covered by varying thicknesses of lead were exposed. Agreement between the two sets of results was excellent.

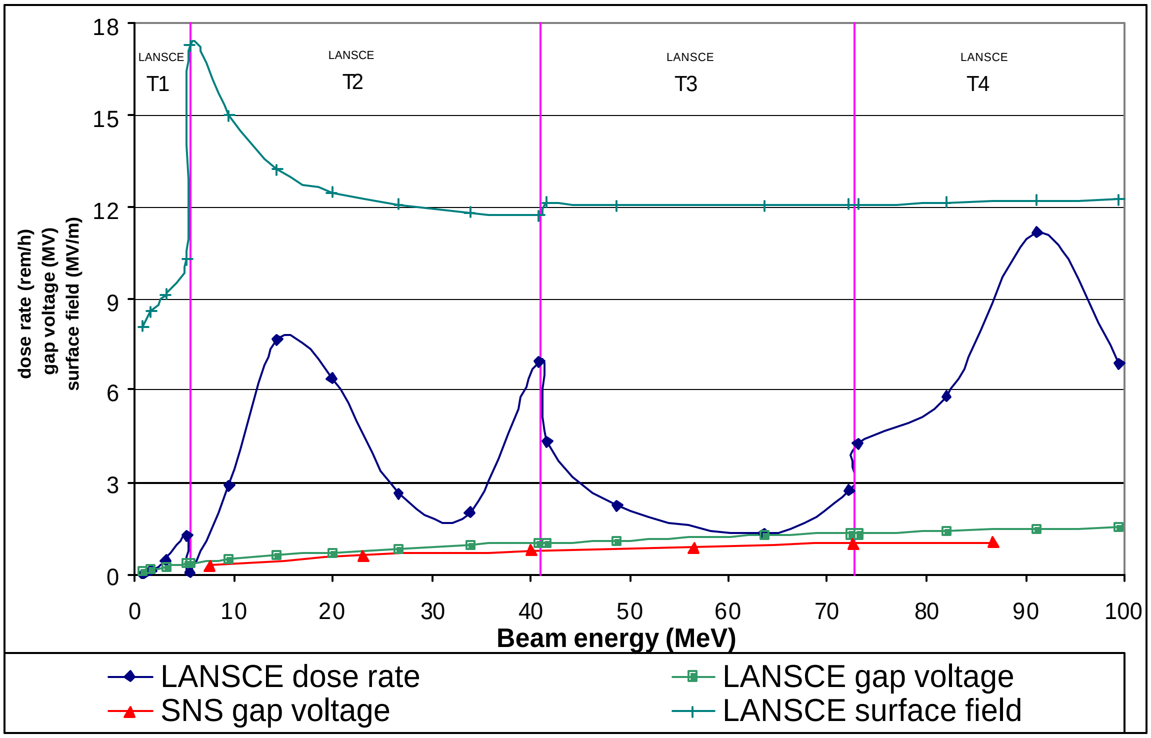

Figure 3.: DTL SUPERFISH data and measured dose rate as a function of beam energy

				Dose (rem in 2 hr exp.)		Dose Rate (mrem/h)
Sequence	**TLD No.**	**Function**	**Location**	**Shallow**	**Deep**	
5	36343	Background		0.00	0.00	**0**
18	37041	Background		0.00	0.00	**0**
2	36214	Conditioning	Tank 1-2 Seam *	0.00	0.00	**0**
17	36937	Conditioning	Bottom at RF Inlet *	0.35	0.24	**4860**
19	37066	Conditioning	High E Tank 2 Seam *	0.00	0.00	**0**
21	37072	Conditioning	Beam Axis After T2 *	0.13	0.13	**2640**
3	36288	Low-E Face	Top	0.15	0.15	**75**
16	36907	Low-E Face	Tunnel-side	0.11	0.11	**53**
4	36305	Low-E Face	Bottom	0.02	0.02	**11**
1	36207	Low-E Face	Wall-side	0.10	0.10	**52**
22	37088	High-E Face	Top	3.26	3.26	**1630**
23	37101	High-E Face	Tunnel-side	5.40	5.40	**2700**
24	37147	High-E Face	Bottom	0.47	0.47	**237**
25	37153	High-E Face	Wall-side	1.27	1.27	**635**
30	37410	High-E Face	Center	4.77	3.82	**1910**
37	37486	High-E Face	Mid-face	4.45	4.45	**2225**
6	36391	Top Penetration	T2 - DT 7	2.02	2.02	**1010**

Table 1. LANSCE DTL Radiation Levels - July 2001, tanks 1 & 2 only.

		ORNL TLDs		Shallow	Deep	Dose Rate
				(rem in 2 hr exp.)		(mrem/h)
7	36392	Top Penetration	T2 - DT 17	5.15	5.15	**2574**
8	36407	Top Penetration	T2 - DT 27	5.05	5.05	**2525**
9	36437	Top Penetration	T2 - DT 35	4.69	3.54	**1770**
10	36490	Top Penetration	T2- DT 43	1.97	1.97	**987**
11	36580	Top Penetration	T2 - DT 49	1.79	1.58	**790**
12	36590	Top Penetration	T2 - DT 58	1.90	1.50	**750**
13	36596	Top Penetration	T2 - DT 63	2.25	2.25	**1126**
33	37419	Post-coupler	Drift Tube 9	4.82	4.82	**2410**
34	37420	Post-coupler	Drift Tube 29	11.28	11.28	**5640**
35	37427	Post-coupler	Drift Tube 45	4.07	3.50	**1750**
36	37452	Post-coupler	Drift Tube 59	1.50	1.50	**750**
20	37070	Ion Pump	Penetration at DT 46	2.94	2.94	**1468**
38	37498	Tank Wall	T1 – Low E Seam	0.05	0.05	**25**
39	37499	Tank Wall	T1 - 3'	0.19	0.19	**95**
40	37522	Tank Wall	T1 - 6' (with ORNL)	0.90	0.90	**450**
41	37527	Tank Wall	T1 - 9'	2.56	2.56	**1280**
42	37580	Tank Wall	Tank 1-2 Seam	0.15	0.15	**75**
43	37581	Tank Wall	T2 – 3' DT 6	5.82	5.82	**2910**
44	37582	Tank Wall	T2 - 6' DT 10	5.78	5.78	**2890**
45	37599	Tank Wall	T2 - 9' DT 14	13.44	10.92	**5460**
46	37602	Tank Wall	T2 – 12' DT 18	14.48	14.48	**7240**
47	37629	Tank Wall	T2 – 15' DT 22	15.34	15.34	**7670**
48	37659	Tank Wall	T2 – 18' DT 26	14.49	13.24	**6620**
49	37684	Tank Wall	T2 – 21' DT 29	15.35	15.35	**7675**
50	37692	Tank Wall	T2 – 24' DT 32	12.75	12.75	**6375**
51	37737	Tank Wall	T2 – 27' DT 35	7.91	7.91	**3953**
28	37353	Tank Wall	T2 – 30' DT 41	7.42	6.64	**3320**
57	37861	Tank Wall	T2 - 33' DT 43.5	5.91	5.25	**2626**
60	38080	Tank Wall	T2 – 36' DT 46	3.92	3.92	**1960**
56	37859	Tank Wall	T2 – 39' DT 49	4.18	2.96	**1481**
27	37352	Tank Wall	T2 – 42' DT 51	6.20	6.20	**3100**
59	37935	Tank Wall	T2 – 45' DT 54	4.10	4.10	**2050**
58	37930	Tank Wall	T2 - 48' DT56 w ORNL	4.16	3.37	**1685**
26	37308	Tank Wall	T2 – 51' DT 58	2.54	2.54	**1270**
29	37381	Tank Wall	T2 - 54' DT 60.5	2.12	2.12	**1060**
15	36750	Tank Wall	T2 - 57' DT 62.5	4.83	4.83	**2417**
14	36744	Tank Wall	T2 – 60' DT 65	17.14	13.91	**6957**
32	37417	Tank Bottom	At RF Inlet	7.89	7.89	**3945**
31	37411	Tunnel Wall	17' from Tank, at RF In	0.70	0.70	**350**
52	37765	Energy Package	Bare	7.62	7.62	**3811**
53	37767	Energy Package	1/8" Lead	2.18	1.44	**720**
54	37773	Energy Package	1/4" Lead	1.71	0.83	**415**
55	37788	Energy Package	1/2" Lead	0.58	0.58	**289**

Table 1. (continued) : LANSCE DTL Radiation Levels - July 2001, tanks 1 & 2 only

				Dose		Dose Rate
				(rem in 2 hr exp.)		(mrem/h)
Sequence	**TLD No.**	**Function**	**Location**	**Shallow**	**Deep**	
61	179530	Background		0.00	0.00	**0**
62	178251	Tank 1	Middle of Tank	0.71	0.72	**360**
63	179431	Tank 2	Tank at Drift Tube 56	2.24	2.61	**1305**
64	178240	Tank 2	Bottom At RF Inlet	8.69	5.63	**2815**
65	178265	Energy Package	Bare	7.31	7.10	**3550**
66	178816	Energy Package	1/4" Lead	0.68	0.90	**450**
	15411	Siemens EPD	Bottom At RF Inlet	5.50	5.14	**2570**
	15304	Siemens EPD	Wall of Room	0.74	0.71	**355**
			* Conditioning involved a 5-minute exposure			
			Instead of a 2-hour exposure			

Table 1. (continued) : LANSCE DTL Radiation Levels - July 2001, tanks 1 & 2 only

Sequence				**Dose Rate (deep)**
	TLD#	Location	Z (feet)	**rem/h**
1	102374	Background		**0**
2	102558	Tank 3 wall section 1, EW-DT4	1	**4.346**
3	103644	Tank 3 wall section 1, DT6-DT7	5	**3.43**
4	107291	Tank 3 wall section 1, DT9-DT10	9	**2.26**
5	107971	Tank 3 wall section 1, DT11-DT12	13	**1.399**
6	109063	Tank 3 wall section 2, DT14-DT15	17	**2.073**
7	113224	Tank 3 wall section 2, DT17-DT18	21	**2.22**
8	114316	Tank 3 wall section 2, DT19-DT20	25	**2.734**
9	115010	Tank 3 wall section 2, DT22-DT23	29	**2.649**
10	120689	Tank 3 wall section 3, DT24-DT25	33	**1.725**
11	132150	Tank 3 wall section 3, DT26-DT27	37	**1.458**
12	143865	Tank 3 wall section 3, DT28-DT29	41	**1.308**
13	147929	Tank 3 wall section 3, DT30-DT31	45	**1.789**
14	148620	Tank 3 wall section 4, DT33-DT34	49	**1.439**
15	150588	Tank 3 wall section 4, DT35-DT36	53	**1.073**
16	160041	Tank 3 wall section 4, DT37-DT38	57	**1.665**
17	163481	Tank 3 wall section 4, DT40-EW	61	**2.72**
18	165620	Tank 4 wall section 1, EW-DT4	65	**4.264**
19	168836	Tank 4 wall section 1, DT5-DT6	69	**2.876**
20	170352	Tank 4 wall section 1, DT7-DT8	73	**3.237**
21	171793	Tank 4 wall section 1, DT9-DT10	77	**2.638**
22	175287	Tank 4 wall section 2, DT11-DT12	81	**3.549**
23	176268	Tank 4 wall section 2, DT13-DT14	85	**5.039**
24	178191	Tank 4 wall section 2, DT15-DT16	89	**5.787**
25	178247	Tank 4 wall section 2, DT17-DT18	93	**7.375**
26	178540	Tank 4 wall section 3, DT19-DT20	97	**6.692**
27	180699	Tank 4 wall section 3, DT21-DT22	101	**5.211**
28	181253	Tank 4 wall section 3, DT23-DT24	105	**10.284**

Table 2.: LANSCE DTL Radiation Levels - August 2001, tanks 3 & 4 only

Sequence				Dose Rate (deep)
	TLD#	Location	Z (feet)	rem/h
29	181412	Tank 4 wall section 3, DT25-DT26	109	**11.181**
30	182015	Tank 4 wall section 4, DT26-DT27	113	**12.469**
31	182080	Tank 4 wall section 4, DT29-DT30	117	**15.319**
32	182945	Tank 4 wall section 4, DT31-DT32	121	**12.235**
33	188720	Tank 4 wall section 4, DT33-EW	125	**6.882**
34	191055	Tunnel wall T3 halfway S2 @15' from tank wall	23	**0.245**
35	203316	Tunnel wall T3 halfway S3 @15' from tank wall	38.5	**0.17**
36	203711	Tunnel wall T3 halfway S4 @11' from tank wall	54	**0.145**
37	203839	Tunnel wall T4 halfway S1 @11' from tank wall	72	**0.408**
38	206407	Tunnel wall T4 halfway S2 @11' from tank wall	86.5	**0.727**
39	209529	Tunnel wall T4 halfway S4 @9' from tank wall	116	**1.679**
40	211193	Background		**0**

Table 2.(continued): LANSCE DTL Radiation Levels - August 2001, tanks 3 & 4 only

7. Appendix: Notes on Dose Measurements using TLDs

Deep dose is measured through a 1000 mg/cm2 teflon shield (about the density of human tissue). Shallow dose is measured through a thin mylar window (15 mg/cm2). The statistical and systematic uncertainty in reading a significant dose from the dosimeter is about +- 5%. However, the dose conversion formula used for TLDs assumes the dosimeter was on a human when the dose was recorded, and the registered dose in these measurements may be 20% to 30% below the true value due to the lack of an assumed reflecting body behind the dosimeter. The few dosimeters placed on walls in these measurements are probably fairly accurate, while those on the tank probably underestimate the true dose by 25%.

8. Acknowledgements

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