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Radiological Analysis of the National Ignition Facility

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Abstract

The National Ignition Facility (NIF) will be capable of providing a laser output pulse at 0.35 μm wavelength with an energy of 1.8 MJ and a power of 500 TW. The NIF will house a multi-beamline, Nd-doped-glass laser capable of delivering such pulses into a target chamber. In the target chamber, a positioner will center a target containing fusion fuel (a deuterium-tritium mixture) for each ignition shot. Diagnostics in the chamber will provide the test data (e.g., neutron and x-ray yields). The NIF baseline case would result in deuterium-tritium (DT) neutron yields of about 10^{16} to 10^{19} per fusion shot. The baseline fusion shots would use 2 Ci of tritium per capsule, with an annual input of about 600 Ci (60 mg). The resulting anticipated annual airborne emissions would consist of approximately 10 Ci of tritium and small amounts of activated air species. The NIF shielding configuration would limit the direct and skyshine radiation intensities around the facility to less than 0.1 rem/y on site and to less than 0.001 rem/y off site. This report presents the results of atmospheric transport calculations for tritium and activated air emissions; neutron and secondary gamma-ray shielding calculations; and results of benchmark studies for validating the EPA CAP88-PC code (for the transport of tritium) and the Lawrence Livermore National Laboratory neutron-photon transport code TART. All calculations were normalized to the annual baseline case of 1.4×10^{20} DT-fusion neutrons. Tritium emissions were normalized to 10 Ci/y. Radiological analyses show that normal NIF operations would result in off-site radiation intensities that would represent insignificant increases over the natural background radiation intensity. The NIF is a national facility, and the DOE has not completed the site evaluation process. Although the results presented in this report are for LLNL, the analytical approach is applicable to any site.

I. Summary

The following major conclusions can be drawn from this report:

A. Dose/Risk to the Public

During normal NIF operations, small amounts of tritium and activated air products would be released into the atmosphere. Based on calculations and past experience, the expected annual emissions resulting from fusion experiments would be as follows:

- ^3H , 10 Ci.
- ^{13}N , 18.5 Ci.
- ^{16}N , 35 Ci.
- ^{17}S , 0.29 Ci.
- ^{40}Cl , 0.31 Ci.
- ^{41}Ar , 3.28 Ci.
- ^{14}C , 9.25×10^{-5} Ci.

Table 1 gives the effective dose equivalent and potential health effects to a maximally exposed member of the public from these emissions. The dose rate to a maximally exposed person would be 7.5×10^{-6} rem/y, and the corresponding risk of fatal cancer would be 3.8×10^{-9} per year. This added exposure rate would be insignificant in relation to both the natural background radiation intensity of 0.3 rem/y and the DOE/EPA air emission standard of 0.01 rem/y. Similarly, the increase in individual fatal cancer risk would be insignificant in relation to the natural fatal cancer incidence rate of 1.96×10^{-3} per year.

B. Collective Population Dose and Health Effects

Table 1 also gives the projected dose and health effects for the year-2000 population residing within 80-km radius of Lawrence Livermore National Laboratory (LLNL). The collective dose rate of 0.14 person-rem/y shown in Table 1 is insignificant in relation to the 2.3×10^6 person-rem/y natural background dose rate received collectively by the same population. The average dose rate to the population would be 1.9×10^{-8} rem/y, which is 6×10^{-8} times the natural background intensity. A collective dose rate of 0.14 person-rem/y would result in 7×10^{-5} extra fatal cancers over the lifetime of the exposed population per year of NIF operation, again 6×10^{-8} times the value expected from natural background radiation.

C. Radiation Intensities at the Site Boundary

The projected radiation intensity from all sources (of which the greatest contributor is skyshine) at the closest site boundary due to normal NIF operations would be about 1.3×10^{-4} rem/y (see Table 2), an insignificant addition to the natural background intensity.

Table 1. Projected off-site individual and population dose and potential radiologically related health risks resulting from NIF air effluents.

Exposure category	NIF operation		Natural background		
	Dose rate (rem/y)	Fatal cancer risk (deaths/y)	Dose rate (rem/y)	Fatal cancer risk (deaths/y)	Total deaths/y ^a
Maximally exposed person	7.5E-6	3.8E-9	0.3	1.5E-4	1.96E-3
Population within 80 km					
Collective	0.14	7.0E-5	2.3E6	1.1E3	1.5E4
Average	1.9E-8	9.3E-12	0.3	1.5E-4	1.96E-3

^a Based on the average cancer death rate in the United States (Moore, 1993). Since the California rate is 1.53 deaths per 1000 (Moore, 1993), about 12,000 annual natural cancer deaths would be expected for the year 2000 for the population within an 80-km radius of LLNL.

Table 2. Projected radiation exposure rates 330 m north of the NIF (assumed distance to nearest site boundary).

Radiation	Effective dose rate (rem/y)	DOE/EPA standard (rem/y)	% of standard
Air effluents	0.000006	0.01	0.06
Direct/skyshine	0.00012	—	—
Total	0.00013 ^a	0.1	0.13

^a Total effective dose rate at the nearest site boundary would be indistinguishable from the average natural background radiation intensity, which is about 0.3 rem/y.

D. Occupational Exposure Rates

The residual radioactivity in various structural components of the target chamber, space frame, concrete, and optics, and the residual activation products and tritium in the chamber, would together constitute the primary sources of occupational exposure. As shown in Table 3, the occupational doses will be kept at least an order of magnitude lower than the current DOE administrative guide and the projected DOE/ICRP radiation standards.

E. Skyshine

For a 1.22-m-thick concrete roof, the neutron and gamma-ray skyshine dose rate at the nearest site boundary (fence post) would be about 0.00012 rem/y for an annual yield of 1.4×10^{20} neutrons. This dose rate is insignificant in relation to the DOE/ICRP limit of 0.1 rem/y to members of the public. A cost-benefit analysis will be performed to optimize the target room shielding configuration. For instance, an additional 0.3-m-thick concrete roof would reduce the skyshine dose by more than a factor of 10.

F. Atmospheric Transport Code Validation

We have conducted benchmark studies that indicate that the CAP88-PC transport code is

likely to overpredict tritium concentrations in the Livermore Valley by a factor of 1.1 to 3.2. This agreement between the measured and predicted results is quite remarkable given the complexity of transport processes and of meteorological and terrain conditions.

G. Monte Carlo Code Validation

Theoretical and experimental data indicate that (when particles are properly weighted in the problem) the neutron-photon transport code TART tends to overpredict transmission in the forward direction by a factor of 2 for very thick (2 to 2.5 m) concrete shields. The actual effectiveness provided by concrete shielding would therefore be greater than that based on TART calculations.

Details regarding atmospheric tritium and activated air emissions, dose calculations, shielding calculations, and benchmark studies are presented in the following sections. Neutronics for the NIF are also discussed in a separate document (Latkowski and Tobin, 1993). Selection of nuclear radiation shielding materials around the NIF vacuum chamber that would provide attenuation equivalent to 30 cm of polyethylene will be discussed in a separate document. The radiation detection and measurement instrumentation that will be used to validate projected exposure rates and airborne radioactivity concentrations will be listed in the NIF Siting Requirement Document.

Table 3. Projected occupational radiation doses from normal NIF operations.

Exposure category	Effective dose rate (rem/y)	DOE/ICRP standard (rem/y)	% of standard
Prompt	0.01	—	—
Residual activity (design criteria)	0.18	—	—
Tritium	0.01	—	—
Total	0.20	2–5 ^a	4–10

^a DOE 5480.11, 5 rem/y (occupational limit); ICRP 60, 2 rem/y (recommended average over 5-year period).

II. Atmospheric Emissions

The National Ignition Facility will conduct several hundred fusion experiments per year to achieve ignition and gain. Experiments with DT shots can result in atmospheric releases of small amounts of tritium (primarily during cleanup) and activated air from the target room. Table 4 summarizes exposure rates from postulated tritium and activated-air emissions. Code validation studies indicate that the dose estimates given in Table 4 are overpredicted on the average by a factor of 1.1 to 3.2. As shown in Table 4, the projected maximum and average exposure rates are well below the EPA air emission standard of 0.01 rem/y. Emissions at these intensities will have negligible added impact on the environment and human health, so LLNL's existing environ-

mental monitoring program would provide more than adequate coverage for NIF operations.

A. Tritium

Each DT filled capsule will contain less than 0.2 mg of tritium, so the annual tritium input to the NIF would be about 60 mg (600 Ci). With proper containment and scrubbing of the vacuum system exhaust before venting to the atmosphere, the amount of tritium expected to be released annually from normal operations is estimated to be about 10 Ci. Experience with the Nova laser system indicates that about 0.5% of tritium input into the chamber is adsorbed on interior surfaces of the chamber, optics, and diagnostic components; this would amount to 3 Ci release per 600 Ci input. Tritium releases from the Rotating Target Neutron Source II (RTNS-II) were about 70 Ci/y per 250,000 Ci throughput (this scales to about 0.2 Ci release per 600 Ci throughput). The first Joint European Torus (JET) tritium experiment (Huguet et al., 1992) indicated that approximately 4.5 Ci were released through the stack and possibly another 7.5 Ci were held up in tokamak components following 977 Ci injection into the tokamak (which scales to 3 to 7 Ci release per 600 Ci input). Experience with RTNS-II, Nova, and JET suggests that tritium emissions from the tritium scrubber system would be less than 0.01 Ci/y. Tritium releases from NIF would therefore result from desorption of tritium (primarily during chamber cleanup and maintenance) from contaminated materials.

The current exposure rate limit for individual members of the public from all sources is 0.1 rem/y (U.S. DOE, 1990; ICRP, 1990); the airborne contribution is limited to 0.01 rem/y (U.S. EPA, 1992a). To determine compliance with the emissions standard, EPA requires that the dose to members of the public be calculated using EPA-approved computer models or procedures. In this report we use the EPA-approved computer code CAP88-PC (U.S. EPA, 1992b) for dose and risk calculations.

In the atmospheric transport calculations, we used on-site meteorological data (wind direction, wind speed, atmospheric stability, etc.) for the years 1989 through 1991. This set of data is very complete and is of higher quality than those for

Table 4. Projected exposure rates for the year 2000 due to postulated annual tritium and activated-air emissions from NIF operations.

Emission	Effective dose equivalent	
	Individual (rem/y) ^a	Population (person-rem) ^b
Tritium ^c	9.2E-7	1.3E-1
Activated air	6.6E-6	1.2E-2
Total	7.5E-6 ^d	1.4E-1 ^e

^a Maximum potential dose equivalent from all exposure pathways to a member of the public living 0.8 km NNE of LLNL Bldg. 391.

^b Dose equivalent for the projected population (7.56 million) living within an 80-km radius of LLNL.

^c Tritium emissions will occur primarily during cleanup. The expected emissions will be less than 1% of past annual emissions from LLNL and SNL (see Table 15), and will be about the same as those experienced at the first JET tritium experiment, conducted in November 1991. The air activated species are assumed to be purged at a rate of 1% of the target room volume per minute, the same rate that was designed for the Nova laser. Based on the openings in the target chamber for laser beams and diagnostics, about 13% of the primary neutrons leak into the target room. The neutron-induced radioactivity is normalized to 1.4×10^{20} DT neutrons.

^d Calculated lifetime fatal cancer risk for the maximally exposed individual for a lifetime (70 y) continuous exposure is 2.6×10^{-7} .

^e Calculated collective population health risk (deaths/y) is 7.0×10^{-5} ; average individual risk is 9.3×10^{-12} . Average dose rate for the population is 1.9×10^{-8} rem/y, approximately 0.000006% of the natural background radiation intensity.

previous years (Gouveia, 1992). The average annual mixing height was assumed to be 750 m. As an example, Table 5 gives the wind and frequency-of-weather category for 1991, based on Livermore climatology data (Lamson et al., 1992). The use of annual diffusion statistics is quite appropriate for the NIF operation, because the shots will be distributed over the entire year.

In the model we considered expected air effluents for two cases, with and without the tritium scrubber or effluent recovery system. In both cases we assumed that tritium emission from the target vessel was exhausted via a 0.15-m-diam, 27-m-high stack with an exit air velocity of 1 m/s. The rates of tritium diffusion, deposition, etc., were calculated using the local climatology (e.g., see the wind rose data given in Table 5). We further assumed an average air temperature of 15°C and rainfall of 34 cm/y. The terrain was assumed to be flat. This oversimplified assumption tends to give conservative dose estimates; see Sec. VI for more detailed discussion of our code validation studies. Table 6 gives the food chain consumption values used in the code for the ingestion pathway dose contribution. The terrestrial food chain pathway dose was calculated using the methods specified in NRC Regulatory Guide 1.109.

The baseline population density within an 80-km radius of LLNL is based on the 1990 census report (Educational Data Services, 1991). For calculation, the population within the 80-km area was distributed into regions formed by concentric circles and radial lines at 22.5° intervals. Population projections in these regions were conservatively derived from 1970–92 growth rate statistics (Table 7) (State of California, 1990, 1991, 1992). The higher growth rate was used in segments where counties overlapped. The population increase within the 16-km-radius area, however, was based on the growth rates of Livermore and Pleasanton. Table 8 shows the projected population distribution within this area for the year 2000 (first year of NIF operation). The 1990 baseline population of 6.38 million is projected to increase to 7.56 million by the year 2000. This value was used for assessing the potential individual and public exposures and risks from routine and design-basis-accident releases.

Table 9 gives the calculated annual dose equivalents for a maximally exposed individual, and for the population collectively, within an 80-km radius area of LLNL. The tissue weighting factors used by EPA are based on ICRP 30.

Table 10 gives the corresponding projected health risks. In obtaining the values in Table 10, the EPA dose-to-risk conversion factor of 4×10^{-4} fatal cancers/rem for the exposed population was replaced with the more conservative value of 5×10^{-4} fatal cancers/rem recommended by ICRP (ICRP, 1991); this latter value is based on the best available scientific judgment and recommendations made by the National Research Council (NRC, 1990).

The exposure risks were calculated for two cases: one without the tritium recovery system, which can result in 600 Ci/y release, and one with the system, for which the expected release (primarily from cleanup and maintenance operations) is about 10 Ci/y. The maximum calculated dose rates to a member of the public for releases of 10 and 600 Ci/y are 9.2×10^{-7} and 5.5×10^{-5} rem/y, respectively (see Table 9). The year-2000 collective population dose rate without the tritium recovery system would be 7.7 person-rem/y (corresponding to an average of 10^{-6} rem/y per person, or about 0.0003% of the average natural background exposure rate). With the tritium recovery system, the population dose rate drops to 0.13 person-rem/y. In both cases, the postulated added exposure rates and the corresponding health risks are insignificant in relation to the natural radiation exposure rates (2.3×10^6 person-rem/y) or the 16.4% background lifetime fatal cancer rate (National Academy of Sciences, 1980).

B. Environmental Monitoring for Air Emissions

Without any measures to reduce air emissions, the maximum calculated dose rate to members of the public is less than 0.0001 rem/y. Since the resulting dose rate from emissions is below the EPA threshold (40 CFR 61), the NIF would be exempt from the requirement that emissions be continuously monitored. Nevertheless, the concentration of tritium in air and the total emitted through the NIF stack would be sampled on a real-time basis with ionization chambers and passively with silica gel columns. Similarly, the maximum projected concentrations for a 600 Ci/y release of tritiated water vapor (total annual input) in the Livermore Valley, based on Fig. 1, would be significantly less than

Table 5. 1991 wind speeds and stability parameters used in the CAP88 model, based on 10-m LLNL MET tower data (Lamson et al., 1992).

Arithmetic average wind speed (m/s)

Wind towards	Pasquill stability class						
	A	B	C	D	E	F	G
N	0.855	1.167	1.844	1.589	1.429	0.875	0.813
NNW	1.167	1.650	2.625	1.724	0.948	0.857	0.692
NW	0.809	1.275	3.820	0.759	0.674	0.721	0.715
WNW	0.878	0.700	1.000	0.578	0.625	0.635	0.665
W	1.358	0.967	1.200	0.600	0.631	0.649	0.677
WSW	1.409	2.014	3.300	0.672	0.831	0.984	0.765
SW	1.747	2.495	3.344	3.229	1.545	1.067	0.781
SSW	1.487	2.687	3.517	3.950	1.144	1.006	0.754
S	1.383	2.546	4.377	6.420	1.180	1.135	0.793
SSE	1.267	2.060	3.716	4.200	1.289	1.433	0.768
SE	1.143	1.806	2.400	1.229	0.843	0.742	0.936
ESE	1.504	2.004	3.240	2.922	1.550	0.900	0.722
E	1.629	2.733	3.897	4.055	1.662	0.923	0.982
ENE	1.756	2.557	3.857	3.632	1.594	1.071	0.842
NE	1.292	2.236	3.626	3.977	1.923	0.952	0.832
NNE	1.235	1.163	2.208	3.276	2.214	0.979	0.862

Frequency of stability class

Wind towards	Pasquill stability class						
	A	B	C	D	E	F	G
N	0.0242	0.0132	0.0198	0.3473	0.3516	0.0791	0.1648
NNW	0.0366	0.0081	0.0163	0.2358	0.2439	0.0935	0.3659
NW	0.0391	0.0142	0.0178	0.1922	0.1779	0.1673	0.3915
WNW	0.0299	0.0066	0.0000	0.1794	0.2027	0.1528	0.4286
W	0.0686	0.0108	0.0072	0.0578	0.2130	0.1625	0.4801
WSW	0.1406	0.0437	0.0063	0.0781	0.1531	0.1813	0.3969
SW	0.0827	0.0968	0.2025	0.2623	0.1408	0.0687	0.1461
SSW	0.0944	0.0969	0.2179	0.3317	0.0605	0.0412	0.1574
S	0.1688	0.0997	0.1790	0.3529	0.0512	0.0435	0.1049
SSE	0.2707	0.1105	0.1768	0.1215	0.0497	0.0663	0.2044
SE	0.4422	0.1156	0.0748	0.0476	0.0476	0.0816	0.1905
ESE	0.2836	0.0873	0.1564	0.2145	0.0727	0.0400	0.1455
E	0.1281	0.0974	0.2297	0.4757	0.0290	0.0111	0.0290
ENE	0.1451	0.1313	0.1953	0.4319	0.0429	0.0113	0.0421
NE	0.0415	0.0311	0.1030	0.6929	0.0768	0.0159	0.0387
NNE	0.0190	0.0089	0.0280	0.5056	0.3389	0.0313	0.0682
Total	0.0993	0.0645	0.1241	0.3978	0.1280	0.0513	0.1350

Table 6. Agricultural data used in calculating the ingestion dose contribution from the food pathway.

	Vegetables	Milk	Meat
Fraction home produce	0.076	0.000	0.008
Fraction from assessment area	0.924	1.000	0.992
Fraction imported	0.000	0.000	0.000

Beef cattle density (number/km ²)	8.81E-02
Milk cattle density (number/km ²)	2.85E-02
Land fraction cultivated for vegetable crops	1.18E-02

Table 7. Population growth in Alameda and neighboring counties from 1970 to 1992.

County	Pop., 1980	Pop., 1990	Growth/y, 1980-92	Pop., 1970	% gain, 1970-92	Growth/y, 1970-92
Alameda ^a	1,109,500	1,313,300	0.0142	1,073,000	22.40	0.0092
Contra Costa	658,500	836,900	0.0202	557,500	50.12	0.0186
San Joaquin	350,200	502,000	0.0305	292,100	71.86	0.0249
San Francisco	680,500	728,700	0.0057	713,200	2.17	0.0010
Santa Clara	1,300,200	1,531,800	0.0138	1,072,600	42.81	0.0163
Stanislaus	267,700	393,400	0.0326	195,800	100.92	0.0322
Marin	222,700	237,000	0.0052	207,000	14.49	0.0062
San Mateo	588,100	670,100	0.0109	557,100	20.28	0.0084
Solano	237,200	364,700	0.0365	105,000	247.33	0.0582
Subtotal	5,414,600	6,577,900	0.0164	4,773,300	37.81	0.0147

City	1992	1980	Growth/y ^b
Livermore	59,400	48,349	0.0173
Pleasanton	52,600	35,160	0.0341

^a Includes Livermore and Pleasanton population data.

^b Used for projecting population within 10 miles from LLNL. Year-2000 population projections in various regions were based on the growth rates for the relevant counties. The more conservative growth rate was used where counties overlapped.

Table 8. Population distribution projected for the year 2000. The distance intervals are from LLNL to the boundaries of regions formed by 22.5 deg radial lines and concentric circles.

Direction	Distance interval (km)										
	0–1.6	1.6–3.2	3.2–4.8	4.8–6.4	6.4–8	8–16	16–32	32–48	48–64	64–80	0–80
N	12	112	0	0	265	0	14,281	33,871	6,989	3,120	58,650
NNW	12	1	2,308	0	0	67	2,063	147,762	2,136	239,967	394,316
NW	12	69	6,220	1,494	0	1,364	17,657	305,217	168,268	134,699	635,000
WNW	47	1,227	31	17	0	213	85,681	265,833	556,541	158,971	1,068,561
W	989	3,176	4,727	6,868	11,951	34,541	94,038	351,608	486,247	577,365	1,571,510
WSW	551	7	3,448	4,906	11,192	20,078	137,086	148,218	352,663	21,969	700,118
SW	119	202	5	114	14	10	98,649	337,746	151,401	4,477	592,737
SSW	499	57	0	0	0	9	22,999	694,530	379,753	65,000	1,162,847
S	552	0	0	0	0	86	0	55,081	73,644	68,482	197,845
SSE	151	155	0	0	0	0	282	6	71	3,080	3,745
SE	261	0	0	0	0	0	281	18	80	13,536	14,176
ESE	75	0	0	382	0	0	830	3,863	19,362	70,554	95,066
E	151	0	0	0	0	137	12,100	10,908	210,190	193,145	426,631
ENE	24	0	0	0	49	0	40,966	80,987	13,904	5,469	141,399
NE	0	0	0	0	4	57	727	152,365	282,384	16,362	451,899
NNE	24	0	0	0	0	0	8,752	1,568	8,347	28,766	47,457
Total	3,479	5,006	16,739	13,781	23,475	56,562	536,392	2,589,581	2,711,980	1,604,962	7,561,957

Table 9. Calculated dose equivalents for the maximally exposed individual and for the collective year-2000 population within an 80-km radius area of LLNL for 10 Ci/y (unless noted otherwise) tritium emission. The maximally exposed individual is assumed to reside 800 m north northeast of the National Ignition Facility.

Organ	Maximum individual (rem/y)	Collective population (person-rem/y)
Gonads	9.03E-07	1.22E-01
Breast	9.03E-07	1.22E-01
Red bone marrow	8.96E-07	1.22E-01
Lungs	9.03E-07	1.23E-01
Thyroid	8.96E-07	1.22E-01
Bone surfaces	7.11E-07	9.65E-02
Remainder	9.75E-07	1.43E-01
Effective dose	9.17E-07	1.28E-01
Effective dose (600 Ci)	5.50E-05	7.68E+00

Pathway contributions to the effective dose equivalents

Pathway	Maximum individual (rem/y)	Collective population (person-rem/y)
Ingestion	8.04E-08	6.08E-02
Inhalation	8.37E-07	6.69E-02
Air immersion	0.00E+00	0.00E+00
Ground surface	0.00E+00	0.00E+00
Internal	9.18E-07	1.28E-01
External	0.00E+00	0.00E+00
Total	9.18E-07	1.28E-01

Table 10. Projected health risks for maximally exposed individual and for the year-2000 area population within an 80-km radius area of LLNL for 10 Ci/y tritium emission.

Cancer type	Maximally exposed individual total lifetime fatal cancer risk ^a	Total collective population fatal cancer risk (deaths/y) ^a
Leukemia	3.55E-09	6.80E-06
Bone	1.58E-10	3.01E-07
Thyroid	5.09E-10	9.78E-07
Breast	4.43E-09	8.46E-06
Lung	5.60E-09	1.08E-05
Stomach	3.76E-09	8.00E-06
Bowel	2.01E-09	4.34E-06
Liver	3.93E-09	7.54E-06
Pancreas	2.68E-09	5.13E-06
Urinary	1.46E-09	2.80E-06
Other	3.26E-09	6.26E-06
Total	3.14E-08	6.14E-05 ^b

^a Based on the ICRP 60 population risk factors.

^b Population average equals 8.1×10^{-12} fatal cancers/y for a release rate of 10 Ci/y.

the environmental compliance value of 1.5×10^3 pCi/m³ (U.S. EPA, 1992c).

With the scrubber system in operation, the expected tritium concentrations (Fig. 1) would be well below the current detection limit of 2 pCi/m³ for tritium (Guthrie, 1992). Since the code overpredicts the concentrations on average by a factor of 1.1 to 3.2, the actual concentrations in the Livermore Valley air are expected to be well below 1 pCi/m³.

The expected radioactivity in air, vegetation, groundwater, etc., in the Livermore Valley and at the site boundary will have negligible added impact on the environment and human health, so LLNL's existing environmental monitoring program would provide more than adequate coverage for NIF operations.

C. Air Activation

Air in the NIF target room between the target chamber shield and the concrete walls is subject

to neutron activation. In the neutron transport calculations, the air interface was modeled radially from 4 to 14 m with a 0.6-m-thick concrete shell on the outside to account for room scattering. It was assumed that 13% of the DT neutrons produced in the target chamber emerge into the room air through the beam and diagnostics ports. The air composition was assumed to be that of dry air (78.4 at.% N, 21.12 at.% O, and 0.48 at.% Ar). The neutron transport calculations were performed using the TART code and its associated neutron cross section libraries (Plechaty and Kimlinger, 1976). All results were normalized to a baseline annual fusion yield of 1.4×10^{20} DT neutrons.

Table 11 lists important radionuclides produced in the target room air. Release of activated gases is assumed to occur at a rate of 1% of room volume per minute through the building stack.

The stack emissions can be calculated from the differential equations describing the change

Figure 1. Projected tritium concentrations vs distance and direction in Livermore Valley air for a 10-Ci/y release through the NIF stack. LLNL meteorological data used in the calculations were averages for the years 1989 through 1991.

Table 11. Neutron-induced radioactivity produced in target room air, based on 1.4×10^{20} DT neutrons per year with 13% transmission through the target chamber openings.

Nuclide	Half-life	Production (Ci/y)	Stack emissions (Ci/y)
^{13}N	9.99 min	146	18.5
^{16}N	7.13 sec	20450	35.0
^{37}S	5.06 min	4.2	0.29
^{40}Cl	1.42 min	15.3	0.31
^{41}Ar	1.83 hr	5.36	3.28
^{14}C	5730 y	9.27E-5	9.27E-5
^3H	12.33 y	1.12E-3	1.12E-3

in radioactivity in the target room following a fusion shot:

$$\frac{dA}{dt} = -C_e v_e - \lambda A$$

$$\frac{dC}{dt} = -C_e \frac{v_e}{v_r} - C\lambda$$

$$C = C_0 e^{-(\alpha+\lambda)t}$$

$$R = \int_0^\infty C_0 e^{-(\alpha+\lambda)t} v_e dt = \frac{A_0 \alpha}{\alpha + \lambda}$$

where A = activity in the room at time t ; C_e = effluent discharge concentration; v_e = effluent volume flow rate; λ = radioactive-decay constant, v_r = room volume, C = room concentration at time t ; $C_0 = A_0/v_r$; and R = amount discharged following a fusion shot from $t = 0$ to $t = \infty$. Table 11

shows stack emissions based on these equations, with $v_e/v_r \equiv \alpha = 0.01 \text{ min}^{-1}$.

In dose and risk calculations, we assumed the same values for food consumption, population density, meteorology, and other parameters as those used in Sec. II.A for tritium dose and risk calculations. Table 12 gives the calculated annual doses from activated-air emissions. The maximum projected individual and population dose

rates are $6.6 \times 10^{-6} \text{ rem/y}$ and $1.2 \times 10^{-2} \text{ person-rem/y}$, respectively. This is insignificant in relation to the emission standards and the natural background radiation intensity. The added health risks at these exposure rates are insignificant: the maximum individual total lifetime fatal cancer risk, weighted over 70 y of exposure, is 2.3×10^{-7} , and the total collective population risk is 6×10^{-6} deaths per year.

Table 12. Projected year-2000 doses due to postulated activated-air emissions from the NIF. With a 2-hr holdup, the dose drops by a factor of 10.

Nuclide	Emission amount (Ci) ^a	Effective dose equivalents		
		Individual (rem/y) ^b	Population (person-rem/y) ^c	Site boundary (rem/y) ^d
¹³ N	18.5	4.8E-6	3.8E-3	3.0E-6
¹⁶ N	35.0	2.2E-23	—	1.0E-15
³⁷ S	0.29	1.5E-7	—	4.2E-7
⁴⁰ Cl	0.31	1.2E-8	—	2.6E-7
⁴¹ Ar	3.28	1.6E-6	8.5E-3	4.3E-7
¹⁴ C	9.25E-5	1.4E-11	2.2E-5	—
³ H	1.12E-3	9.6E-11	1.2E-5	—
Total		6.6E-6	1.2E-2	4.1E-6

^a The air activated species are released at a rate of 1% of the target room volume per minute. It is assumed that 13% of the primary neutrons leak into the target room air. Results were normalized to 1.4×10^{20} DT neutrons.

^b This dose equivalent is the maximum potential dose from all pathways to a member of the public residing at 800 m north northeast of LLNL Bldg. 391. The effective dose equivalents resulting from internal and external exposures have been weighted over the irradiated organs and tissues.

^c The dose equivalent is for the projected population (7.56 million people) residing within an 80-km radius of LLNL. The effective dose equivalents resulting from internal and external exposures have been weighted over the irradiated organs and tissues.

^d The closest site boundary is 330 m north of Bldg. 391. At this location, the ratio χ/Q of the atmospheric dispersion to the source term is about $1.26 \times 10^{-6} \text{ s/m}^3$, and the annual average wind speed is 1.1 m/s.

III. Neutron Skyshine and Direct Radiation

A. Skyshine

"Skyshine" is radiation at the receptor location, generally on the ground, arising from collisions with air nuclei by radiation transmitted into the atmosphere through the building roof. Radiation transmitted through the building walls is considered "direct" radiation. Both skyshine and direct radiation can contribute to appreciable exposure rates around and above the NIF. Table 13 lists the numbers of projected NIF experiments at various yields (Campbell et al., 1992); calculations are normalized to an average annual yield of 1.4×10^{20} DT neutrons. The facility is expected to operate for 20 to 30 years.

Table 14 gives the neutron source parameters used for neutron transport calculations. The DT neutron source is defined in terms of polar and azimuthal angles that represent about 13% of the 4π solid angle. The target room measures 30.5×15.2 m, with a height of 26 m. The roof is 1.22-m-thick reinforced concrete, and the walls are 1.83-m-thick reinforced concrete. Figure 2 shows the calculated skyshine dose at ground level as a function of distance from the center of the NIF target room, again for an annual yield of 1.4×10^{20} DT neutrons. The maximum dose occurs at about 50 m from the center of the room. The sum of skyshine and direct exposure rates will remain less than 0.1 rem/y; the value could

go considerably lower, depending on cost-benefit and social factors. The shielding design philosophy will be the same as that used for RTNS-II, which allowed unlimited access outside the target cells. Depending on the final shielding configuration, access to the roof may be controlled during the DT shots to minimize personnel exposure.

B. Direct Radiation

The intensity of direct radiation outside the building was calculated with the assumption that the chamber is 0.10-m-thick Al, surrounded by a nonflammable material that provides neutron shielding equivalent to 0.30 m of polyethylene, and that the walls are 1.83-m-thick ordinary concrete. Figures 3, 4, and 5 give the transmission of neutrons and secondary gammas in these materials. Outside the building, the radiation intensity is due primarily to secondary gamma rays. Figure 2 shows the direct and skyshine contributions. With this shielding configuration, the maximum radiation intensity is significantly less than the NIF exposure criterion (0.1 rem/y) for unrestricted access around the facility. Further dose reduction can be achieved by using cost-benefit analysis to optimize the shielding configuration.

Table 13. Fusion yield associated with the NIF experiments.

Fusion yield per experiment	Number of experiments	Annual fusion yield	
		Energy (MJ)	Neutrons
100 kJ	100	10	3.6E18
5 MJ	35	175	6.2E19
20 MJ	10	200	7.1E19
Total	145	385	1.4E20

Table 14. Neutron source distribution (cosines of polar angles between which neutrons are emitted) used in skyshine calculations. The azimuthal angle is from 0 to 2π .

$\cos \theta_1$	$\cos \theta_2$
0.92	0.943
0.854	0.877
0.627	0.674
0.515	0.562
-0.943	-0.92
-0.877	-0.854
-0.674	-0.627
-0.562	-0.515

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Figure 2. Projected neutron skyshine and direct radiation intensities (maximum) outside the NIF. The skyshine contribution is from radiation transmitted through the 1.83-m-thick concrete roof. The direct contribution is from radiation transmitted through the 0.10-m-thick Al chamber, 0.30 m of polyethylene, and 1.83-m-thick concrete walls. (In practice, a nonflammable material that provides neutron shielding equivalent to 0.30 m of polyethylene will be used; a possible example is ordinary concrete containing 2.5 wt% boron.)

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Figure 3. Neutron and secondary gamma-ray transmission in 0.10-m-thick Al chamber and 0.30 m of polyethylene.

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Figure 4. Neutron and secondary gamma-ray transmission in 1.83-m-thick concrete shield after passing through the materials indicated in Fig. 3.

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Figure 5. Transmission of neutron and secondary radiation through 0.10-m-thick Al chamber, 0.30 m of polyethylene, and a 1.83-m-thick concrete shield. (Contains the data of Figs. 3 and 4 on a single plot.)

IV. Occupational Exposure Rates

Annual prompt dose rates were calculated for areas inside and outside the NIF. For a 40-hour workweek, the dose rate in all areas would be less than 0.01 rem/y. The dose rates in the control room and war room would be less than 0.0024 rem/y (Latkowski and Tobin, 1993). Dose rates inside the building are dominated by direct radiation. Some areas where doses are likely to be higher would be restricted during the high-yield shots.

Occupational exposure would arise mainly from the residual radioactivity in various structural components of the NIF chamber, space

frame, target debris, optics, and concrete. As already shown in Table 3, occupational doses will be kept at least a factor of 10 below the DOE administrative guide and the current DOE/ICRP occupational standards. Calculations show that unlimited entry to the target area can be permitted 1 day after a 100-kJ shot, 5 days after a 5-MJ shot, and 6 days after a 20-MJ shot (Latkowski and Tobin, 1993). Limited-duration entry could begin sooner. Occupational radiation doses would be controlled in accordance with applicable DOE orders and policies and with LLNL ALARA principles.

V. Decontamination and Decommissioning

After 20 years of NIF operation, the facility might require decontamination in conjunction with decommissioning (D&D). Since there would be less than 10 Ci of residual tritium in the vessel, and the residual radioactivity in the structural and shielding components would be similar to that normally associated with accelerator facilities, D&D of the NIF would present no unusual problems.

The amount of neutron-induced radioactivity on the interior surfaces of the vessel would be governed primarily by the activation of target materials that, after vaporization, are deposited on the internal surfaces of the chamber. Calculations (Latkowski and Tobin, 1993) show that after 20 years of operation, the surface dose rate in the vessel from such material would be 0.04 rem/hr.

This assumes the use of a cryogenic system made of stainless steel and copper. If the cryosystem is made of aluminum, the residual radioactivities are reduced to insignificant values. The design criterion dose rate of 0.2 rem/y will be used for cleaning, dismantling, and removal of activated components.

Neutron activation calculations (Latkowski and Tobin, 1993) for the vessel, shields, concrete walls, and space frame show that the residual long-term activity would be dominated by ^{54}Mn (312-day half-life) and ^{59}Fe (45-day half-life) in the rebar in the concrete walls. Under a worst-case scenario, the residual radiation intensity at the wall surfaces would be 0.002 rem/hr. This intensity would present no unusual radiological hazards for D&D operations.

VI. Environmental Transport of Tritium: Validation of the EPA CAP88-PC Code

A. Air Pathway

The CAP88-PC code is a modified version of the AIRDOS-EPA program for calculating environmental transport of atmospheric emissions. The uncertainties in the predicted results for the Livermore Valley can be determined by using the high-quality, well-documented data for LLNL and SNL tritium emissions, local meteorology, environmental monitoring (air, vegetation and soil), and emission parameters.

Table 15 gives the past annual tritium emissions from LLNL and SNL; Table 16 gives the tritium stack dimensions and effluent emission velocity, which are used for plume rise (Wong, 1989; Brekke, 1992). Local meteorology data for years 1989 through 1991 (Gouveia, 1992) were used for plume dispersion calculations. EPA-recommended values were used for tritium deposition, precipitation scavenging (based on rainfall), and plume depletion.

In the source term, we used the HTO emissions, because HTO is the major contributor to the measured tritium concentrations in soil, collected water vapor, and vegetation. Tables 17 through 20 give the results of atmospheric transport calculations and the measured air

Table 16. LLNL (Bldg. 331) and Sandia (TRL) stack and emission velocity parameters used in the tritium atmospheric dispersion calculations.

Parameter	LLNL	TRL
Stack height (m)	30	30
Stack diameter (m)	1.18	1.4
Gas exit velocity (m/s)	9	1.5

concentrations on- and off-site (Lawrence Livermore National Laboratory, 1986–1991). Figure 6 shows tritium sampling locations.

The benchmark calculations indicate that, on average, the CAP88-PC code overpredicts the tritium concentrations within a 10-km radius by a factor of 1.1 to 3.2. Between 10- and 80-km radius, one would expect greater dispersion because of hills, mountains, ridges, ravines, changes in ground elevation (which varies from 200 to 90 m from east to west), and urban heating. The results predicted by the code are therefore fairly conservative.

Table 15. Tritium emissions from LLNL and SNL for the past 6 years. Emissions are divided into two categories: tritiated water vapor (HTO) and tritium gas.

Year	Tritiated water (Ci)			Tritiated water plus gas (Ci)		
	Total	LLNL	SNL	Total	LLNL	SNL
1986	1,403	774	629	2,014	1,254	760
1987	1,899	1,329	570	4,578	2,751	1,827
1988	2,688	1,641	1,047	5,573	3,983	1,590
1989	2,210	1,554	656	3,786	2,952	834
1990	944	700	244	1,577	1,282	295
1991	1,028	678	350	1,573	1,110	463
Total	10,172	6,676	3,496	19,101	13,332	5,769
Average	1,695	1,113	583	3,184	2,222	962

Table 17. Distances (in kilometers) and directions of sampling locations (Fig. 6) from LLNL and TRL stacks, and predicted and measured tritium concentrations in air in the Livermore Valley for the years 1989 to 1991.

Distance (km) from	XRDS	VET	ZON7	ALTA	LCCY	FIRE
Bldg. 331	2.1 SE	1.9 SW	3.7 NE	9.1 NNE	5.6 W	3.1 W
TRL	1.3 E	1.6 W	4.4 NE	10.0 NNE	5.9 WNW	3.3 WNW

Tritium concentrations in air (Ci/m ³)						
	XRDS	VET	ZON7	ALTA	LCCY	FIRE
1989, calculated						
TRL	1.96E-11	1.89E-11	8.11E-12	3.33E-12	6.45E-12	1.16E-11
LLNL	3.38E-12	2.28E-11	1.85E-11	6.96E-12	9.41E-12	1.42E-11
Total	2.29E-11	4.18E-11	2.66E-11	1.03E-11	1.59E-11	2.58E-11
1989, measured						
	8.00E-12	1.40E-11	1.40E-11	5.00E-12	4.00E-12	7.00E-12
1990, calculated						
TRL	7.74E-12	3.48E-12	2.17E-12	6.73E-13	8.51E-13	1.62E-12
LLNL	3.33E-12	7.55E-12	7.99E-12	1.91E-12	2.00E-12	3.77E-12
Total	1.1E-11	1.1E-11	1.0E-11	2.6E-12	2.8E-12	5.4E-12
1990, measured						
	4.70E-12	7.10E-12	8.70E-12	5.50E-12	2.90E-12	3.80E-12
1991, calculated						
TRL	1.03E-11	4.72E-12	3.33E-12	1.27E-12	1.72E-12	3.28E-12
LLNL	1.39E-12	7.37E-12	7.31E-12	2.36E-12	1.76E-12	2.88E-12
1991, measured						
	3.40E-12	8.00E-12	5.60E-12	3.50E-12	3.30E-12	4.20E-12

Table 18. Predicted-to-measured tritium concentration ratio for the off-site tritium sampling stations.

Year	XRDS	VET	ZON7	ALTA	LCCY	FIRE
1989	2.87	2.98	1.90	2.06	3.96	3.69
1990	2.35	1.55	1.17	0.47	0.98	1.42
1991	3.43	1.51	1.90	1.04	1.06	1.47
Average	2.88	2.02	1.66	1.19	2.00	2.19

Table 19. Distances (in kilometers) and directions of sampling locations (Fig. 6) from LLNL and TRL stacks, and predicted and measured tritium concentrations in air at the LLNL site boundary for the years 1989 to 1991. See Table 16 for LLNL (Bldg. 331) and Sandia (TRL) stack parameters.

Distance (km) from	SALV	MESQ	CAFE	MET	VIS	COW
Bldg. 331	0.8 ESE	0.9 WNW	0.4 S	1.32 NNW	1.0 ENE	1.3 NNE
TRL	0.9 NE	1.7 NW	0.75 N/NNW	2.3 NNW	1.62 NNE	2.2 NE
Tritium concentrations in air (Ci/m ³)						
	SALV	MESQ	CAFE	MET	VIS	COW
1989, calculated						
TRL	4.16E-11	1.16E-11	1.89E-11	8.32E-12	2.43E-11	1.82E-11
LLNL	1.96E-11	1.23E-11	5.42E-11	8.87E-12	6.16E-11	4.98E-11
Total	6.12E-11	2.40E-11	7.31E-11	1.72E-11	8.59E-11	6.80E-11
1989, measured						
	3.20E-11	2.20E-11	3.20E-11	8.00E-12	3.20E-11	1.80E-11
1990, calculated						
TRL	1.55E-11	2.09E-12	4.95E-12	1.16E-12	6.81E-12	5.42E-12
LLNL	1.35E-11	1.07E-11	1.42E-11	4.22E-12	3.11E-11	2.13E-11
Total	2.90E-11	1.27E-11	1.92E-11	5.38E-12	3.79E-11	2.67E-11
1990, measured						
	1.63E-11	1.04E-11	1.84E-11	6.60E-12	1.77E-11	1.03E-11
1991, calculated						
TRL	2.33E-11	5.55E-12	1.24E-11	3.27E-12	1.22E-11	8.32E-12
LLNL	9.46E-12	5.16E-12	2.13E-11	6.66E-12	2.92E-11	2.56E-11
Total	3.28E-11	1.07E-11	3.37E-11	9.94E-12	4.14E-11	3.39E-11
1991, measured						
	1.43E-11	1.22E-11	1.88E-11	8.57E-12	1.23E-11	1.02E-11

Table 20. Predicted-to-measured tritium concentration ratio for on-site tritium sampling stations.

Year	SALV	MESQ	CAFE	MET	VIS	COW
1989	1.91	1.09	2.29	2.15	2.69	3.78
1990	1.78	1.23	1.04	0.81	2.14	2.59
1991	2.29	0.88	1.79	1.16	3.37	3.32
Average	1.99	1.06	1.71	1.37	2.73	3.23

B. Tritiated Water Vapor Emissions

In the calculations we assumed 100% HTO for routine atmospheric tritium emissions. Experience at LLNL and SNL suggests that this assumption is fairly conservative (see Table 21), causing us to overestimate tritium exposures in the Livermore Valley.

Table 21. Historical tritiated-water-vapor (HTO) to total-tritium-emission ratio for LLNL and SNL.

Year	Tritiated/total emission
1986	0.70
1987	0.41
1988	0.48
1989	0.58
1990	0.60
1991	0.65
Average	0.57

C. Ingestion Pathway

In the tritium dose calculations, the tritium specific activity in vegetation was assumed to be in equilibrium with the atmospheric water. Vegetation- and air-monitoring data for the Livermore Valley (see Figs. 7 and 8) indicate that this is a fairly valid assumption based. No soil data are available near the vegetation- or air-monitoring stations, but there is one area close to the MET tower sampling station that can be used to relate the tritium activity in vegetation to that in soil (see Fig. 9). At this location, the tritium activity in the soil water is appreciably lower than that in the vegetation water. One can therefore conclude with some confidence that uptake of tritium in vegetation (grass) occurs primarily from the tritiated water vapor in the atmospheric air.

Based on these studies, it is reasonable to assume that tritium specific activity is in equilibrium with the water content in leaves of vegetation. This is consistent with the average ratio of 0.8 between water content of vegetation and water vapor content of air observed at the Savannah River Laboratory (Murphy, 1984).

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laboratory (Sandia)

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Figure 6. Tritium sampling locations (LLNL Annual Environmental Report, 1992). (a) LLNL site. (b) LLNL vicinity.

Figure 7. Tritium activity in water content of air at location 7 (Altamont Pass Road; Fig. 6b) and in vegetation near Interstate Highway 580 for years 1986 through 1991.

Figure 8. Tritium activity in water content of air and vegetation (grass) at location 4 (Patterson Pass Road; Fig. 6b) for years 1986 through 1991.

Figure 9. Tritium activity in water content of air, vegetation (grass), and soil near MET tower (ALPW; Fig. 6a) for years 1989 through 1991.

VII. Benchmark Shielding Calculations and Measurements for Deep Penetration of DT Neutrons in Concrete

The neutron and secondary gamma-ray radiation intensity predicted outside the NIF experiment area were calculated using Monte Carlo procedures. The complexity of nuclear collisions and secondary productions and their subsequent multiple scattering makes it difficult to have a great deal of confidence in the predicted results, particularly for 2- to 3-m-thick concrete shields. To bracket the uncertainty, we performed benchmark calculations and compared the results with measurements made at RTNS-II. Based on these benchmark studies, we find that the calculated dose equivalents for 2.13- and 2.44-m-thick concrete shields are overpredicted by about a factor of 2, a fairly good agreement considering the complexity of nuclear interactions. Details of our benchmark studies are presented below.

A. 400-keV Deuteron Accelerator (RTNS-II)

From 1978 to 1989, the RTNS-II accelerator was dedicated to fusion materials research in the Magnetic Fusion Energy program. To improve the fusion material research program, Panel 5 of the Fusion Energy Advisory Committee (FEAC) has encouraged the United States to participate in the development of an international 14-MeV neutron source. The construction of this facility will probably begin in 1996. Although the data presented in this section have direct bearing on NIF, they are equally relevant for validating transport codes used for the design of shielding for fusion reactors or devices or for intense 14-MeV neutron sources.

At RTNS-II, the bombardment of a tritium target by 400-keV deuterons provides a continuous source of 10^{13} 14-MeV neutrons per second. Experimental data (Logan, 1992) indicate that the mean energy of the deuterons that interact with tritium nuclei is about 200 keV. Figure 10 shows the expected dependence of neutron energy on emission angle, calculated with the relativistic energy-momentum relations of Blumberg and Schlesinger (Blumberg and Schlesinger, 1956) for the $D(T,n)^4\text{He}$ reaction. The classical approximation for 200-keV deuterons interacting with tritons gives about the same energy-angle correlations.

Figure 10 shows that the calculated neutron energy agrees quite well with the measurements at 30° and 120° with respect to the incident deuteron direction (Logan and Komoto, 1992). On the strength of this agreement, we used 15.1-MeV neutrons in the forward direction and 14.1-MeV neutrons at 90° for the benchmark calculations. RTNS-II consists of two identical machine rooms and target cells. The exterior concrete walls of the target cells are 2.44 m thick; the concrete roof is 2.13 m thick. The common (middle) concrete wall between the cells is 2.13 m thick. Both cells have 2.44-m-thick concrete doors. The doors were designed to minimize neutron leakage; there are three 10-cm steps on each vertical side and on top of the door with 1.27-cm maximum clearance; the bottom is sloped to give a 15-cm depression over the width of the door with 0.64-cm clearance. Figure 11 shows the 2.44-m-thick door and inside of target area. The interior dimensions of each target cell are $6.1 \times 6.5 \times 4.27$ m.

During the initial runs, only one accelerator was used, so it was possible to make neutron and gamma-ray spectrometry and dose/flux measurements in the adjacent cell and outside the door. Figure 12 shows the locations at which these measurements were made.

B. Flux Measurement Methods

The neutron flux measurements were made with the De Pangher "precision long counter" (PLC) (De Pangher, 1966). The PLC's neutron-energy response from 0.002 to 20 MeV was measured very precisely at LLNL (Slaughter and Rueppel, 1977). The relative response of the PLC is fairly flat from 0.4 to 14 MeV, but it under-responds for neutron energies below a few keV. The thermal neutron component is effectively absorbed by a Cd shield in the detector. The counter's nominal sensitivity to fast neutrons was verified with PuBe and ^{252}Cf neutron sources. During the neutron flux measurements at RTNS-II, the PLC calibration was periodically confirmed in the field with a PuBe source. We also used NE-213 liquid scintillator to measure the neutron spectrum, but because of high noise-to-signal ratio, this data was not used for quantitative purposes.

Figure 10. DT neutron energy vs emission angle for 200-keV deuteron interaction with tritium.

The photon flux outside the 2.13-m-thick shield was determined from pulse-height data taken with a 3×3 NaI(Tl) detector. Because of low photon intensity, the measurements were accumulated over 10^4 -sec intervals. Livermore computer programs (Fuess et al., 1978) were used to convert the experimental pulse-height data to a differential photon energy spectrum, which was then used to calculate dose equivalents. These data were used as a reference for calibrating an ion chamber (STRAD) and micro-R meter, which were used for rapid photon intensity measurements at other locations.

C. Results

Figure 13 shows the calculated neutron spectrum outside the 2.13-m-thick concrete shield. Table 22 gives the elemental composition of the concrete mix, determined by chemical analysis. The theoretical broad peak between 1 and 4 MeV

shown in Fig. 13 was observed with a NE-213 liquid scintillator (see inset in Fig. 13). This peak is due to depression in neutron cross section in concrete in this energy range. The calculated spectrum-weighted flux-to-dose conversion factor for transmitted neutrons with energies from 0.001 to 14 MeV was 1.2×10^{-4} rem/h per $\text{n}/\text{cm}^2\cdot\text{s}$, about the same as what we calculated for the ^{252}Cf neutrons (1.25×10^{-4} rem/hr per $\text{n}/\text{cm}^2\cdot\text{s}$). The thermal flux was based on the thermal-neutron sensitivity of the BF_3 counter. Based on theoretical calculations coupled with experimental measurements with a bare BF_3 tube, we estimate that the neutron dose contribution for energies below 0.001 MeV is about 18%. Table 23 gives the theoretical and experimental results. Figure 14 shows the variation of attenuation with concrete thickness. Experimental measurements indicate that the theory overpredicts the dose equivalent outside the concrete shield by a factor of 2. Figure 15 shows the calculated and measured differential photon energy spectrum

Figure 11. RTNS-II target room.

Table 22. Elemental composition of Livermore concrete mix.

Element	Atomic fraction
H	0.1093
O	0.6062
Fe	0.1220
Mg	1.226E-2
Al	3.18E-2
Na	2.236E-2
Si	0.1752
Ca	2.998E-2

outside the wall. The theory agrees quite well with the observed shape of the spectrum.

Outside the 2.44-m-thick concrete door, the measured neutron and gamma-ray dose equivalent rates are 5 and 6 $\mu\text{rem/h}$, respectively. Since the door is in the forward direction (0°), the incident neutron energy is 15.1 MeV, as described above. At low deuteron bombarding energy (400 keV), neutron emission is fairly isotropic; the intensity is about 10% higher in the forward direction than at 90° . Figure 14 indicates that the ratio of measured neutron and gamma-ray dose equivalents does not change appreciably above about 1.8 m; the theory tends to overpredict the gamma component for a shield thickness of 2.1 m

Table 23. Neutron and secondary gamma-ray intensity outside the 2.13-m-thick shielding wall. All results were normalized to RTNS-II neutron source strength (10^{13} DT neutrons per second). Figure 12 shows locations tabulated here.

Location (cm)		Dose equivalent ($\mu\text{rem/hr}$)			
		Experiment		Theory	
		Neutron	Gamma	Neutron	Gamma
x	y				
0	538	49 (37) ^a	60 (49) ^a	71 ^a	117 ^a
0	638	27	30	—	—
0	738	21	22	—	—
0	838	13	15	14	27
30	538	40	52	—	—
100	538	24	38	—	—
240	538	11	22	—	—
580 ^b	0	5	6	—	—

^a Dose rate averaged over an area with 100-cm radius.

^b Dose equivalents outside the RTNS-II 2.44-m-thick concrete shielding door.

Figure 12. Neutron and secondary gamma intensity measurement locations (plan view). All measurements were made in the horizontal plane containing the target; Table 23 gives precise locations.

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Figure 13. Calculated neutron spectrum outside the RTNS-II 2.13-m-thick concrete shielding wall. Inset: neutron spectrum measured with NE-213.

Figure 14. Attenuation of 14-MeV neutrons and secondary gamma rays through an ordinary concrete shield. The dose equivalent rates are normalized to 10^{13} n/s, the level at which RTNS-II was operating during the measurements.

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Figure 15. Calculated and measured photon spectrum outside the RTNS-II 2.13-m-thick concrete shielding wall.

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