Chapter 11

SURVIVOR SHIELDING

Part A. Nagasaki Factory Worker Shielding

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Introduction

Recent investigations based on conventional chromosome aberration data by the RERF suggest that the DS86 doses received by many Nagasaki factory workers may have been overestimated by as much as 40% relative to those for other survivors in Japanese-type houses and other shielding configurations (Kodama et al. 2001). Since the factory workers represent about 25% of the Nagasaki survivors with DS86 doses in excess of 0.5 Gy (50 rad), systematic errors in their dose estimates can have a major impact on the risk coefficients from RERF studies.

The factory worker doses may have been overestimated for a number of reasons. The calculation techniques, including the factory building modeling, weapon source spectra and cross-section data used in the DS86 shielding calculations were not detailed enough to replicate actual conditions. The models used did not take into account local shielding provided by machinery, tools, and the internal structure in the buildings. In addition, changes in the disposition of shielding following collapse of the building by the blast wave were not considered. The location of large factory complexes may be uncertain, causing large numbers of factory survivors, correctly located relative to each other, to be uniformly too close to the hypocenter. Any or all of these reasons are sufficient to result in an overestimate of the factory worker doses.

During the DS02 studies, factory worker doses have been reassessed by more carefully modeling the factory buildings, incorporating improved radiation transport methods and cross-section data and using the most recent bomb leakage spectra (Chapter 2). Two-dimensional discrete ordinates calculations were carried out initially to estimate the effects of workbenches and tools on worker doses to determine if the inclusion of these components would, in fact, reduce the dose by amounts consistent with the RERF observations (Kodama et al. 2001).

DS86 Factory Shielding Calculations

The current DS86 database for shielding of Nagasaki factory workers was developed by Science Applications International Corporation (SAIC) in 1987 following the publication of the DS86 Report (Kerr 1989, 1998). It was developed using two different factory models that were modeled directly from RERF construction drawings for the Nagasaki factories and shielding histories for the Nagasaki factory workers. One of the factories was a steel frame building with a corrugated steel roof and walls, and the second was a steel frame building with a cement asbestos board roof and walls. The buildings were similar to other light, steel frame industrial buildings found in the United States and Europe.

There were several large factory complexes in Nagasaki within a ground range of 2,000 m (Tables 1 and 2). These included the Mitsubishi Ordnance Factories in Ohashi, the Mitsubishi Steel Works in Mori-machi and Takenokubo, and the Mitsubishi Dockyard in Saiwai-cho. When possible, two identification numbers are given in the tables for each factory building: one is from the coded RERF data for these factory complexes, and the other number is from the 1947 report by the U.S. Strategic Bombing Survey (USSBS 1947). The U.S. Strategic Bombing Survey also provides additional construction details for the steel frame factory buildings at Nagasaki.

A shielding database was constructed by choosing approximately 180,000 random locations to generate an adjoint particle-leakage file for each of the two different factory models (Figure 1 and Table 3). The model designated as “A” had a central cupola on top of the ridge of a corrugated steel roof, and the model designated as “B” had a roof of cement asbestos board with a “saw-toothed” shape. Model “A” was typical of steel frame buildings at the Mitsubishi Steel Works, and Model “B” was typical of steel-frame buildings located at both the Mitsubishi Dockyard and Ordnance Factories.

The two factories were modeled as empty shells with no workbenches, machine tools or other heavy equipment included inside the factory. About 10% variation in transmission factors was found over locations within a factory for a given orientation with respect to the hypocenter, and greater variation in transmission factors at a single location was found for different orientations of the factory. The orientation of each of the factories is specified by an angle between a normal to an exterior wall and a line projected toward the hypocenter as shown in Figure 1. The angle is taken to be positive if the factory is rotated clockwise, and negative if the factory is rotated counter clockwise relative to the line toward the hypocenter. The transmission factors also depend on the roof construction and materials.

If a worker inside a factory was not shielded by heavy equipment and a model was available for the factory (Table 1), then a DS86 estimate of the worker’s dose was made as follows. First, the factory was placed about the worker at the correct ground range and the factory was oriented properly with respect to the hypocenter. Next, the discrete ordinates radiation transport (DORT) forward-mode fluences from the DS86 database for the radiation field in the open and the adjoint leakage fluences from the DS86 database for factory shielding were coupled to obtain the differential energy and angular fluences inside the factory. Finally, the adjoint leakage fluences from the DS86 database for organ doses were coupled with the differential energy and angular fluences inside the factory to obtain the organ doses (as functions of posture and orientation of the body) and in-air kerma (both inside and outside the factory).

Of the 1,041 factory shielding cases in Nagasaki, it was possible to make DS86 estimates for 815 workers (i.e., 664 at the Ordnance Factories, 66 at Plants 1 and 2 of the Steel Works and 85

Table 1. Inventory of factory shielding cases at Nagasaki

Building	Building number		Survivors with shielding histories	Survivors with DS86 estimates
	RERF	USSBS		
Mitsubishi Ordnance Factories, Ohashi Plant				
Final assembly machine shop #1	101	4-22	319	307
Precision machine shop	102	4-21	116	116
Final assembly machine shop #2	103	4-20	45	44
Paravane fabrication shop	104	4-17	8	0
Plate fabrication shop	105	4-4	99	88
Forging shop	106	4-5	30	0
Casting shop	107	4-5A	68	0
Tool shop	108	4-10	48	43
Assembly	109	4-23	19	19
Engineering administration office	110	4-25	32	32
Electroplating shop	111	4-9A	3	0
Pattern shop	112		15	15
Tool room and locker room	113	4-9	1	0
Boiler shop	114	4-11	4	0
Truck shop	115	4-14	1	0
Other locations at Ohashi Plant	198		9	0
Unknown location with Ohashi Plant	199		1	0
Mitsubishi Steel Works, Plant #1, Mori-machi				
Machine shop	201	26-23	59	56
Molding shop	202	26-15	18	9
Forging shop	203	26-19	1	0
Heat treatment shop	204	26-22	1	0
Compressor room	205	26-22	2	0
Mitsubishi Steel Works, Plant #2, Mori-machi				
Molding shop #1	301	26-13	2	0
Boiler shop	302		1	0
Molding shop #2	303	26-11C	1	1
Mitsubishi Steel Works, Plant #3, Takenokubo				
Heat treatment shop	401	31-11	4	0
Forging shop	402	31-1	2	0
Mitsubishi Steel Works, Plant #4, Mori-machi				
Structural Shop	501	26-41	10	0
Other locations within Plant #4	598		1	0
Mitsubishi Dockyard, Saiwai-cho Plant				
Machine shops	601	36-6	68	57
Boiler shops	602	36-1	28	28
Steel casting shops	603	36-16	4	0
Other locations within Saiwai-cho Plant	698		1	0
Other Factory Buildings at Nagasaki	701-711		20	0

Table 2. Nagasaki factory construction data

RERF building number	U.S. Army map coordinates		Ground range (m)	Orientation with respect to hypocenter	Building materials	
	East-West	North-South			Roof	Walls
101	1293.58	1067.37	1312	-10°	Asbestos	Asbestos
102	1293.60	1067.51	1439	-10°	Asbestos	Asbestos
103	1293.62	1067.58	1503	-10°	Asbestos	Asbestos
104	1293.81	1067.63	1558	-3°	Unknown	Unknown
105	1293.91	1067.59	1535	0°	Asbestos	Asbestos
106	1293.90	1067.52	1470	0°	Asbestos	Asbestos
107	1293.89	1067.46	1415	+1°	Asbestos	Asbestos
108	1293.87	1067.41	1366	+1°	Asbestos	Asbestos
109	1293.57	1067.32	1266	-12°	Asbestos	Asbestos
110	1293.68	1067.31	1257	-8°	Asbestos	Asbestos
111	1294.07	1067.53	1514	+6°	Asbestos	Asbestos
112	1294.06	1067.50	1485	+6°	Asbestos	Asbestos
113	1294.03	1067.44	1424	+5°	Unknown	Unknown
114	1293.87	1067.37	1330	+1°	Unknown	Unknown
115	1293.87	1067.33	1294	+1°	Asbestos	Asbestos
201	1293.49	1064.58	1246	+9°	Steel	Steel
202	1293.48	1064.69	1147	+12°	Steel	Steel
203	1293.62	1064.71	1121	+96°	Unknown	Unknown
204	1293.48	1064.64	1192	+101°	Unknown	Unknown
205	1293.51	1064.63	1199	+100°	Steel	Steel
301	1293.52	1064.77	1070	+6°	Steel	Steel
302	1293.52	1064.90	952	+5°	Steel	Steel
303	1293.52	1064.82	1025	+5°	Unknown	Steel
401	1293.34	1064.41	1419	+13°	Unknown	Unknown
402	1293.36	1064.54	1299	+13°	Unknown	Unknown
501	1293.75	1064.56	1263	+119°	Steel	Steel
601	1293.71	1064.09	1690	-150°	Asbestos	Asbestos
602	1293.80	1063.95	1823	-152°	Steel	Steel
603	1293.61	1064.22	1569	-147°	Unknown	Unknown

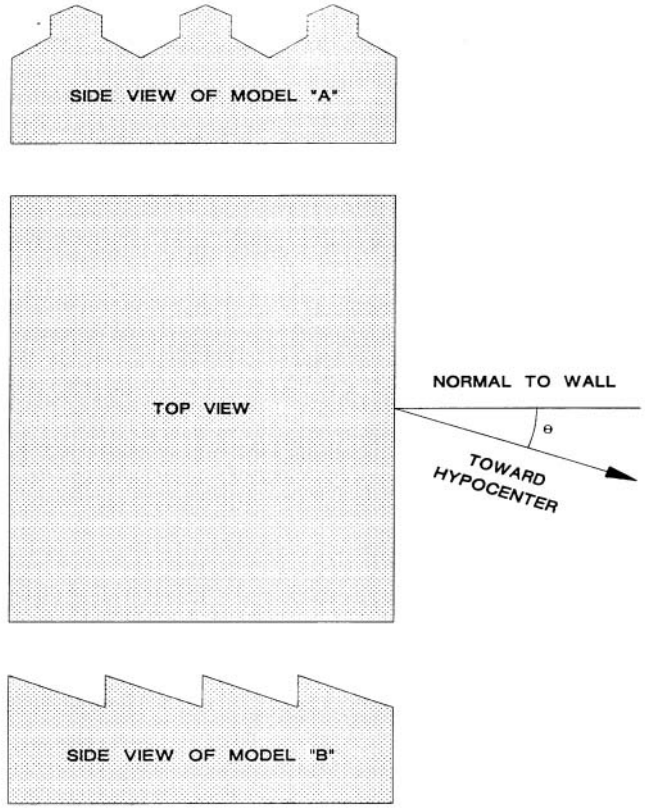


Figure 1. *Schematic showing the rooflines of the two factory models used in DS86 shielding calculations.*

Table 3. Physical characteristics of factory models used in DS86 shielding calculations

Model and component	Material	Mass thickness (g cm^{-2})
Steel Works Factories[a]		
Roof and sidewalls	Steel sheets	0.40
Windows	Glass	1.14
Pillars	Concrete	1.452 - 2.42
Floor	Concrete	24.2
Foundation walls	Concrete	48.4
Ordnance and Dockyard Factories[b]		
Roof and sidewalls	Asbestos board	1.216
Windows	Glass	1.14
Trusses	Steel	31.6
Pillars	Concrete	9.68
Floor	Concrete	24.2
Foundation walls	Concrete	45.6

[a]See Model A in Figure 1.
[b]See Model B in Figure 1.

at the Dockyard). Transmission factors, obtained as averages over all DS86 estimates for factory workers at these three locations, are summarized in Table 4. No DS86 estimates were made for workers who were shielded by large machinery or heavy equipment of any kind.

Table 4. Average factory-transmission factors from DS86

Factory	Radiation component	Transmission factor
Mitsubishi Ordnance Factories, Ohashi Plant	Neutrons	0.94
	Gamma rays	0.75
Mitsubishi Steel Works, Plants #1 and #2	Neutrons	0.99
	Gamma rays	0.81
Mitsubishi Dockyard, Saiwai-cho Plant	Neutrons	0.92
	Gamma rays	0.78

DS02 Factory Shielding Calculations

There is some variation in the accuracy to which individual survivor's doses can be calculated in the factory. The variation is less for survivors who were exposed in the Ohashi Machine Shops, because the machine tools used there were small. Several of the machine tools used in the Ohashi Machine Shops were found at a technical high school in Nagasaki in the 1960s and photographed for future reference, as were several wooden workbenches like those used at the Ohashi Machine Shops. The photographs were used as a source of data for modeling the machine tools used in the DS02 factory shielding calculations.

Figures 2 and 3 show the disposition of buildings at the Mitsubishi Ordnance Factory, Ohashi Plant at Nagasaki at the time of the bombing. The kinds of buildings, construction details and locations of equipment inside the structures were determined from United States Strategic Bombing Survey reports (USSBS 1946, 1947), data provided by the RERF staff at both Hiroshima and Nagasaki (Fujita 2000), and archived photographs and information from other sources such as the Nagasaki Atomic Bomb Museum.

The results reported here are for Building 22, which was the final assembly plant for torpedoes fabricated at the Mitsubishi factory complex. Building 22 also contained the largest number (307/664) of survivors with DS86 dose estimates that were identified in the factory complex. Twenty-four additional buildings are in the immediate vicinity of Building 22 with eleven that were situated between Building 22 and the hypocenter. Only the tissue kerma to which survivors were exposed (kerma) in Building 22 were calculated in this study. Since most of the adjacent buildings are of similar construction and internal layout, kerma to workers within these building can be reasonably well estimated by scaling the Building 22 survivor kerma (see below). All of the buildings shown in Figure 3 lie between 1,250 m and 1,550 m from the hypocenter. Building 22 is nominally 1,350 m from the hypocenter.

Radiation Transport Methods

Two principal radiation transport tools and associated peripheral codes were utilized to reconstruct the Nagasaki factory worker doses: (1) the two-dimensional discrete ordinates

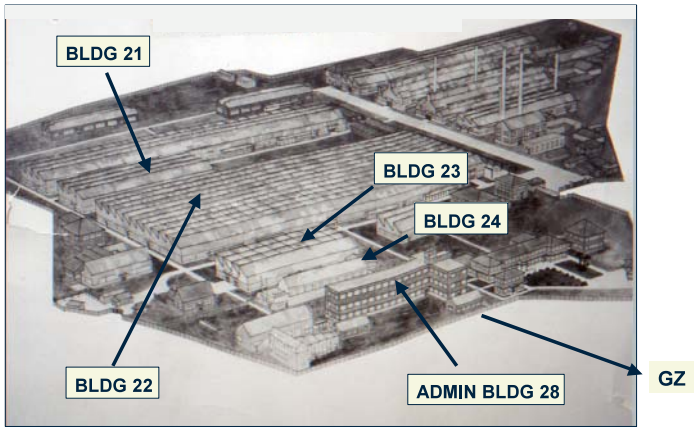


Figure 2. *Aerial view of Mitsubishi Ordnance Factories, Ohashi Plant at Nagasaki.*

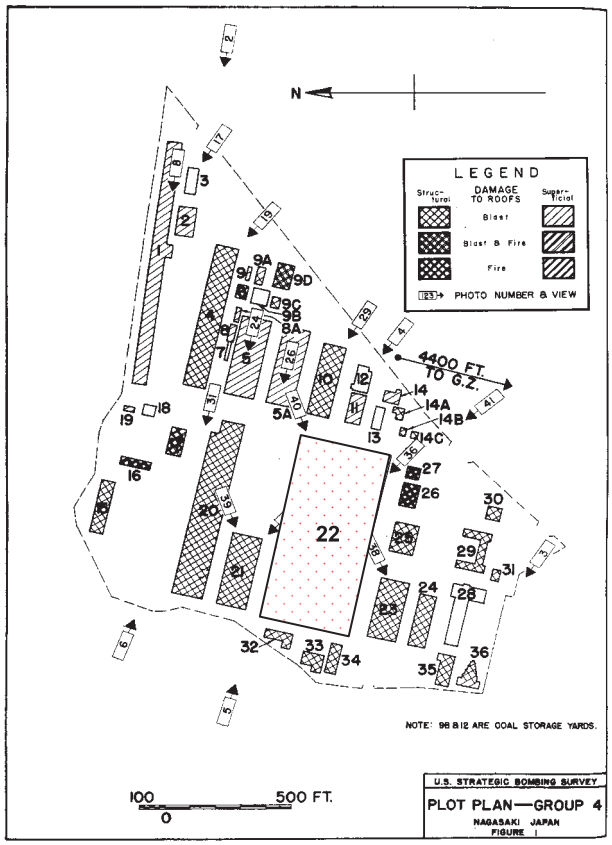


Figure 3. *Plot plan of Mitsubishi Ordnance Factories, Ohashi Plant at Nagasaki.*

transport code DORT (Rhoades 1988), and (2) the Monte Carlo Adjoint Shielding code system MASH (Johnson 1999).

The DORT calculations were carried out using the procedures described in Chapter 3 and also incorporated the GRTUNCL code (DOORS3.2 1998) to generate the uncollided neutron and gamma fluence and first collision sources throughout the geometry mesh to eliminate ray effects in the calculated neutron and gamma-ray fluences. DORT was used for both the preliminary scoping study to estimate the impact of workbenches, tools, and machinery on survivor dose and to generate the air-over-ground radiation environment for use in MASH to obtain the survivor doses at locations inside Building 22.

The Monte Carlo Adjoint Shielding Code System (MASH) was developed by Oak Ridge National Laboratory (ORNL) to facilitate the calculation of radiation protection factors for shielded structures (i.e., the ratio by which the free-field radiation is reduced due to the presence of the structure). MASH was constructed by linking together a discrete-ordinates air-over-ground transport calculation and an adjoint Monte Carlo kerma-importance calculation.

MASH was developed to analyze radiation effects from the detonation of an above-ground nuclear weapon. An air-over-ground transport calculation determines the neutron and photon fluence as a function of energy on a coupling surface surrounding the target. Kerma-importance calculations are then carried out to estimate the radiation at the coupling surface that contributes to the kerma at locations inside the structure. Finally, the fluence is folded with the kerma importance to obtain the desired dose (or kerma) response.

Cross-Section Data and Nagasaki Source Term

The DORT and MASH calculations were performed using ENDF/B-VI multigroup cross-section data derived from the VITAMIN-B6 with 199-neutron and 42-gamma-ray energy fine group cross-section library (Ingersoll et al. 1995). Because MASH incorporates Monte Carlo methods and uses many geometric bodies to describe the factory building and its environs, performing the adjoint Monte Carlo transport in MASH with the 199-neutron and 42-gamma-ray group structure would be prohibitive. Consequently, the ENDF/B-VI fine group library was collapsed to the 46-neutron, 23-photon DABL69 group-structure (Simpson et al. 2001; Ingersoll et al. 1989).

Two-Dimensional Scoping Studies

Two-dimensional radiation transport methods were used initially to determine if the presence of workbenches, machinery, tools, and so forth would reduce the kerma behind the wall sufficiently to proceed with further calculations using detailed modeling of the factory buildings and their contents. To facilitate this initial analysis, the geometric representation of the problem domain was reduced to the least complicated level that would permit testing of the effects of walls and tools.

The computational model used to describe the building walls, tools and workbenches is shown in Figure 4. The problem domain was comprised of an *r-z* region extending 1,353.5 m in the radial direction and 1,500 m along the axis of symmetry above ground level, and 0.5 m below ground level to account for ground shine effects. The Nagasaki weapon output, both neutron and gamma-ray spectra, was represented by a fixed source located on the *z*-axis at 503 m above the ground. The factory outer wall and “interior workbench” were modeled as cylindrical shells located at the outer edge of the problem domain. The DORT code was used to solve this problem

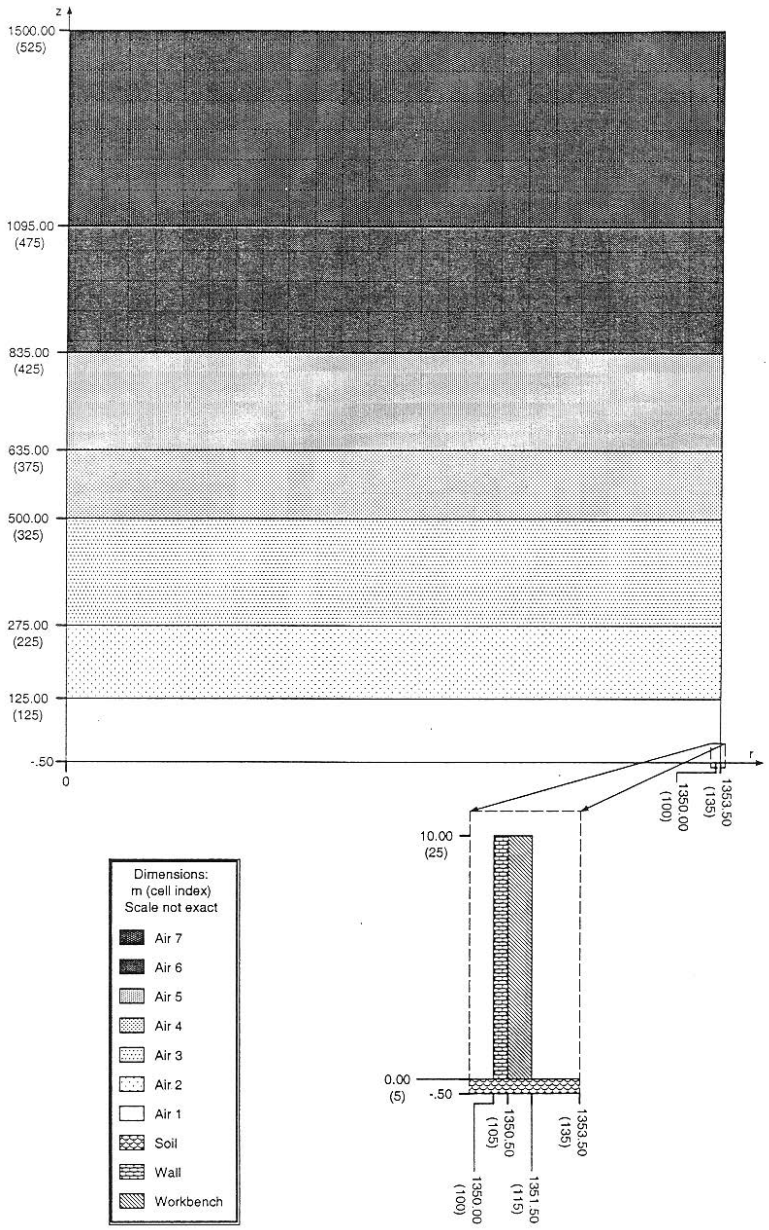


Figure 4. *Two-dimensional calculational model for factory wall-tools scoping study.*

on a 135×525 geometry mesh.

The two-dimensional *r-z* model of the Nagasaki bomb explosion and surrounding area were modeled using cylindrical shell representations of the factory walls and the smeared tools/workbench to set an upper bound on the dose reduction as a function of the tool and workbench material compositions. The weapon source spectrum was also discretized in 46-neutron and 23-gamma groups. The angular anisotropy of scattering was represented by a P_5 Legendre expansion of the scattering cross-section data, while the angular dependence of the angular fluence was discretized along a 240-angle, biased quadrature set. The first collision source was computed using GRTUNCL and processed in DORT to compute the fully collided fluence distribution. All energy groups were converged in DORT to 10^{-4} and the sum of the converged collided and uncollided fluences from the two calculations was folded with fluence-to-kerma conversion factors to generate pointwise maps of group kerma rates.

Cross-section data were taken from Simpson et al. (2001) that were produced specifically for this problem. The compositions of the air layers and ground shown in Figure 4 are summarized in Tables 5 and 6, respectively. Argon cross-section data are not presently included in the VITAMIN-B6 library, so these data were taken from the DABL69 cross-section library. The external wall of the factory building was represented by a mixture of 95% wall material and 5% carbon steel by volume using the material composition shown in Table 7. The density was reduced so that the mixed material density in the wall cell matched the density thickness assigned to the wall. The workbench is represented by a mixture of wood and carbon steel in the ratio 40% and 10%, by volume, respectively, with the remaining 50% representing the voids.

The accuracy of neutral particle transport calculations depends significantly on the precision of the representation of the angular dependence. The large air content and point nature of the source, in relative dimensions, ensure the existence of ray effects. Even with a first-collision source generated via a GRTUNCL calculation, ray effects may still persist in some of the gamma groups. Incorporating the 240-angle biased angular quadrature considerably reduces these ray effects. A P_5 Legendre representation of anisotropic scattering was also used and the resulting fluence and dose profiles exhibited no adverse abnormalities characteristic of ray effects.

Table 5. Atom densities for the air regions

	Nuclide density (atom/barn-cm)			
	^{1}H	^{14}N	^{16}O	Ar
Air 1	1.311×10^{-6}	3.676×10^{-5}	1.052×10^{-5}	2.198×10^{-7}
Air 2	1.231×10^{-6}	3.638×10^{-5}	1.037×10^{-5}	2.176×10^{-7}
Air 3	1.142×10^{-6}	3.593×10^{-5}	1.021×10^{-5}	2.149×10^{-7}
Air 4	1.050×10^{-6}	3.543×10^{-5}	1.003×10^{-5}	2.119×10^{-7}
Air 5	9.590×10^{-7}	3.490×10^{-5}	9.841×10^{-6}	2.087×10^{-7}
Air 6	8.589×10^{-7}	3.426×10^{-5}	9.621×10^{-6}	2.049×10^{-7}
Air 7	7.303×10^{-7}	3.335×10^{-5}	9.312×10^{-6}	1.995×10^{-7}

Table 6. Composition of soil

Nuclide	Density (atom/barn-cm)
H	3.52×10^{-2}
C	1.81×10^{-3}
O	3.86×10^{-2}
Na	2.56×10^{-4}
Al	2.82×10^{-3}
Si	6.81×10^{-3}
Cl	7.51×10^{-6}
K	1.51×10^{-4}
Ca	2.27×10^{-4}
Ti	1.03×10^{-4}
Mn	1.80×10^{-5}
Fe	8.25×10^{-4}
Total (g/cc)	**1.7**

Table 7. Compositions of the transite, wood, steel, glass, and concrete

Nuclide	Transite	Wood	Carbon steel	Plate glass	Concrete
	Density (atom/barn-cm)				
H	3.31×10^{-3}	4.05×10^{-2}	-		7.77×10^{-3}
C	-	2.13×10^{-2}	7.88×10^{-4}		
N		3.66×10^{-4}			
O	4.32×10^{-2}	1.88×10^{-2}	-	4.17×10^{-2}	4.39×10^{-2}
Na				5.74×10^{-3}	1.34×10^{-3}
Mg	3.39×10^{-3}		-		1.49×10^{-4}
Al	3.19×10^{-3}		-		2.39×10^{-3}
Si	6.20×10^{-3}		4.21×10^{-4}		1.58×10^{-2}
S				1.67×10^{-2}	
K					6.93×10^{-4}
Ca	1.89×10^{-2}		-	5.38×10^{-3}	2.92×10^{-3}
Mn	-		3.78×10^{-4}		
Fe	1.34×10^{-3}		8.41×10^{-2}		3.13×10^{-4}
Total (g/cc)	**3.1**	**1.0**	**7.86**	**2.57**	**2.35**

Results

The neutron, gamma, and total kerma inside the factory building as a function of the radial distance from the hypocenter were carefully examined to validate the modeling approach and the associated results. The main purpose of this analysis was to estimate the change in the kerma due to shielding by the simulated workbench and tools. Figure 5 shows neutron and gamma-ray tissue kerma relative to the total kerma at the front of the workbench at different depths through the workbench. The neutron kerma is very small; less than 1% of the gamma-ray kerma.

Fifteen centimeters of this simplified model of the workbench with tools appears sufficient to reduce the tissue kerma by about 40%. This corresponds to 6 cm of solid wood and 1.5 cm of

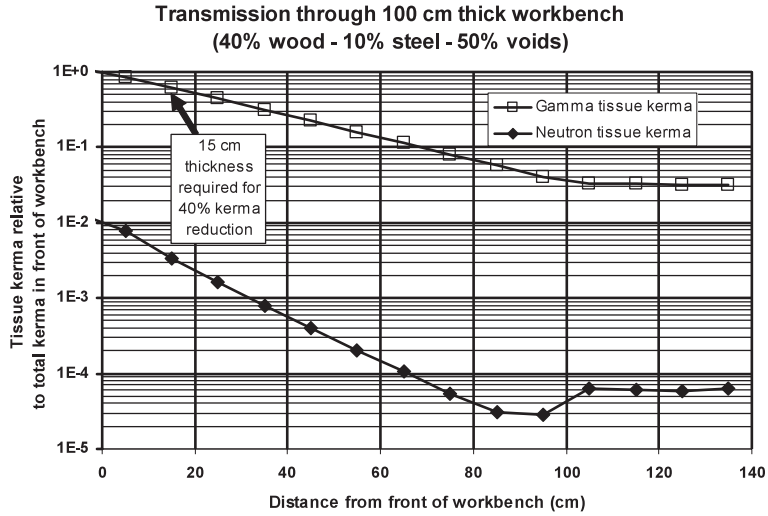


Figure 5. *Ratio of shielded tissue kerma behind workbench inside the factory building with respect to the total tissue kerma incident on front.*

solid carbon steel. These are reasonable material thicknesses for workbenches covered with metal parts. Detailed calculations of the total kerma to individual workers using the more detailed factory wall and workbench geometry with various exposure scenarios are used to investigate whether this result can be confirmed in more accurate models.

Detailed Calculations

The results of the scoping study prompted a more detailed analysis of the kerma to survivors in Building 22. The initial step in the process was to construct a three-dimensional model of the building shown in Figure 2. The dimensions of the building, wall and roof, construction details, interior structures, disposition of workbenches and machinery, and other details were taken from drawings in the USSBS Reports (1946, 1947). The wall material composition was determined from information and construction samples provided by the RERF (Fujita 2000).

Calculation Sequence

Air-over-ground calculations for both the prompt and delayed radiation sources were carried out using the DORT code. The air and ground were represented in *r-z* geometry extending 3,000 m in the radial direction and 2,000 m along the axis of symmetry above ground level, and 0.5 m below ground level. The geometry was divided into 130 radial mesh intervals and 110 axial mesh intervals and was configured to assure that the energy dependent neutron and photon fluence was calculated on a coupling surface that completely surrounded the building geometry for the subsequent adjoint Monte Carlo calculations.

These calculations were also carried out using the 240-angle quadrature to approximate the angular dependence of the neutron and gamma-ray fluence. The angular anisotropy of the scattering was represented using a P_5 Legendre expansion of the scattering cross sections. The

weapon source spectrum was discretized in 46-neutron and 23-gamma groups. The air region was modeled in seven layers using the air mixtures given in Table 5. The ground was taken to be 0.5-m thick and was represented using the soil mixture in Table 6.

The compositions of the building walls and roof were determined from building construction descriptions given in the USSBS Reports and from material samples provided by the RERF. The wall and roof compositions used in the detailed building geometry in MASH are given in Table 7. Also tabulated are the compositions of the concrete floor and glass window panes. The wall thickness was 2.5 cm and 0.5 cm of wood and transite (asbestos cement), respectively. The plate glass thickness was 0.3 cm. The workbench was 5-cm thick wood, and the table top was 76 cm above the floor. The tools, presses, and lathes were carbon steel.

For these detailed calculations the prompt radiation transport calculations were performed using the DS02 prompt and delayed fluences discussed in detail in Chapter 3.

Factory Building Calculations

Figures 6 and 7 show the external features of Building 22 model and a cut-away view showing details of the interior structural components, respectively. These figures were generated from the body descriptors used to create the calculational geometry used in the MASH code and are the actual models used in the adjoint transport calculation. Since Building 22 is very large (224-m wide by 107-m deep relative to the detonation point), only about 60% of the width of the structure was modeled. Most of the known survivor locations were in the portion of the building that was modeled. Replicating the entire structure was deemed to be unnecessary. Incorporating the reduced building geometry model considerably reduced the Monte Carlo calculation time. There were only a few survivors and very little machinery in the portion of the building that was not modeled. The area that was not modeled was most likely used for torpedo storage and/or distribution.

The following convention was used in the calculation of survivor kerma. If the worker was not shielded by a piece of machinery or a workbench, his location in the building was determined and the kerma was calculated with only the building material shielding (walls and roof) taken into account. If the worker was behind or to the side of a workbench, drill press or lathe, the particular piece of equipment was inserted into the calculational geometry, and the kerma to the worker was calculated.

After details of the survivor's location and his proximity to local shielding were determined, the radiation kerma to a factory worker was calculated in two steps.

First, the prompt radiation kerma was calculated using the building configuration shown in Figure 7 including, when necessary, insertion of the appropriate local shielding component shown in Figure 8. Workers were assumed to be standing at the time of the explosion. Some of the delayed radiation contribution to the kerma to the worker occurred before the blast wave hit the building, and some of it occurred after the building was damaged by the blast wave.

Second, after the blast wave hit the building, it was assumed that the worker was knocked to the ground. If the worker was near a piece of machinery, his position on the ground relative to the equipment was the same as it was just prior to the arrival of the blast wave. When the building was hit by the blast wave, parts of the roof may have fallen into the structure and could have landed near or on top of the workers. It had been first thought that the factory survivors were not covered by heavy fallen roof pieces, because they would have been killed or severely injured by

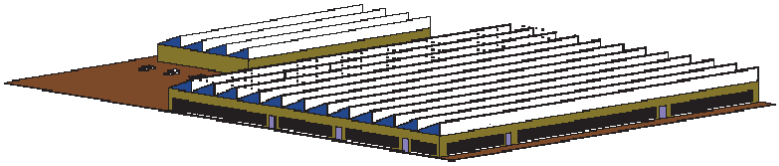


Figure 6. *Calculational model of Building 22.*

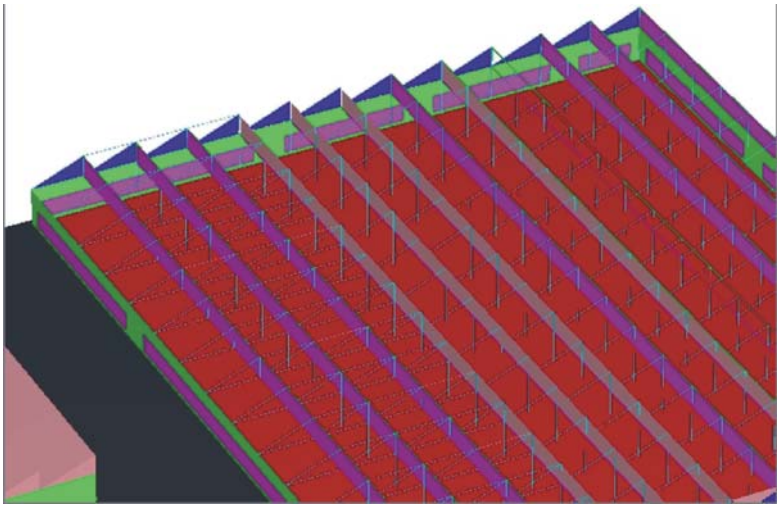
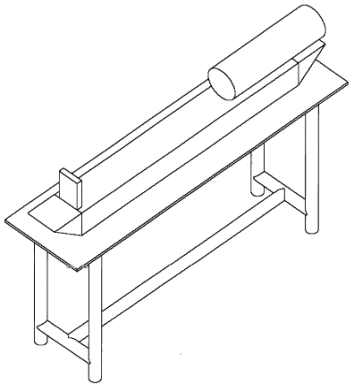


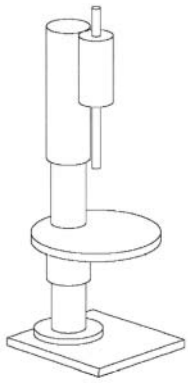
Figure 7*. Interior view of Building 22 (workbenches, machinery and tools not shown).*

them. However, it was not possible to determine for a particular worker whether after the blast he was exposed through an open roof or to what extent he was covered by debris. It was decided to test the delayed radiation calculations with and without the roof in the calculational model for the portion of the delayed kerma that arrives after the blast wave. After both calculations were finished the scenario was rethought and, based on photographs of the factories after the burst, it may be more likely that the roof remained intact or sufficiently covered the survivors enough to have provided the same shielding as if it had stayed intact. The impact of these two roof alternatives will be discussed later. The complete removal of the roof after the blast wave arrives increases the factory kerma by approximately 3%.

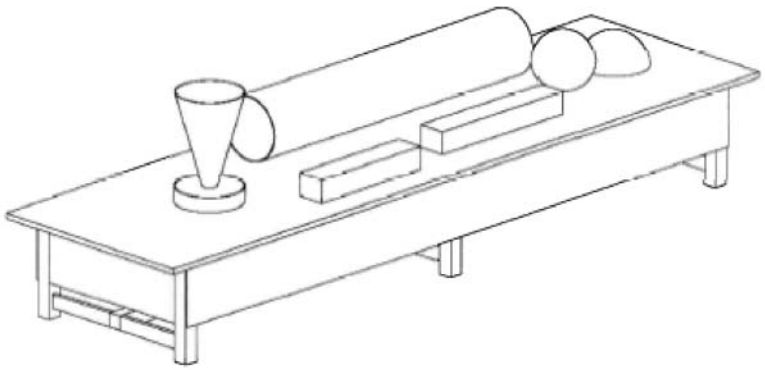
Figure 9 shows the time of arrival of the blast wave from the explosion as calculated using a computer program (Jordan and Welsh 1984) that implements the extensive air-blast data from Glasstone and Dolan (1977). The time of arrival of the blast wave was calculated for an energy yield of 21 kt and burst height of 503 m. Figure 10 shows the fraction of the free-in-air (FIA) tissue kerma from delayed gamma rays and neutrons that arrived at a given ground range prior to the arrival of the blast wave as calculated with the ATR Version 6.1 (ATR6.1) computer program (Dolatshahi et al. 1992). Table 8 gives the curve-fit coefficients for the fraction, F, of the FIA



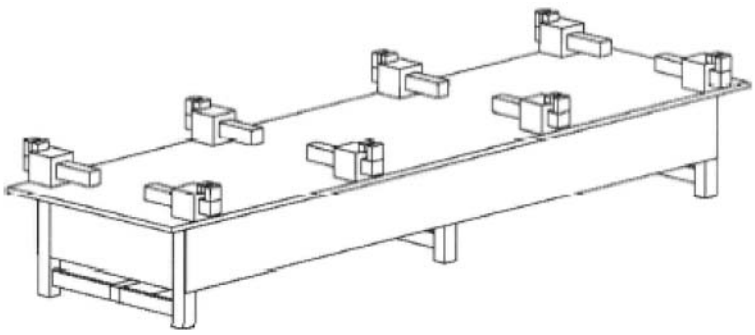
LATHE 40-cm wide, 152-cm long, 76-cm high (table top); all parts are made of metal



DRILL PRESS 76 × 71-cm foot print, 213-cm height



WORKBENCH with parts of torpedo 152-cm wide, 533-cm long, 76-cm high; parts are hollow metal containers; enclosed area beneath the table is also hollow and made of wood



WORKBENCH with vises same dimensions as above; eight metal vises

Figure 8. *Detailed models of lathe, drill press, and workbenches.*

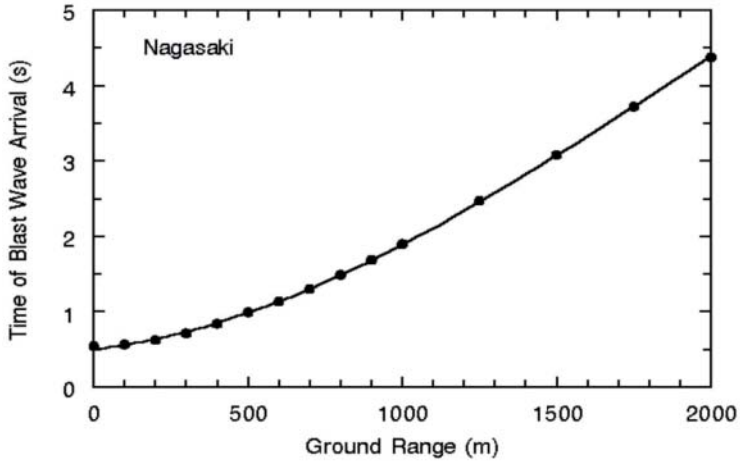


Figure 9. *Time of blast wave arrival as a function of ground range at Nagasaki.*

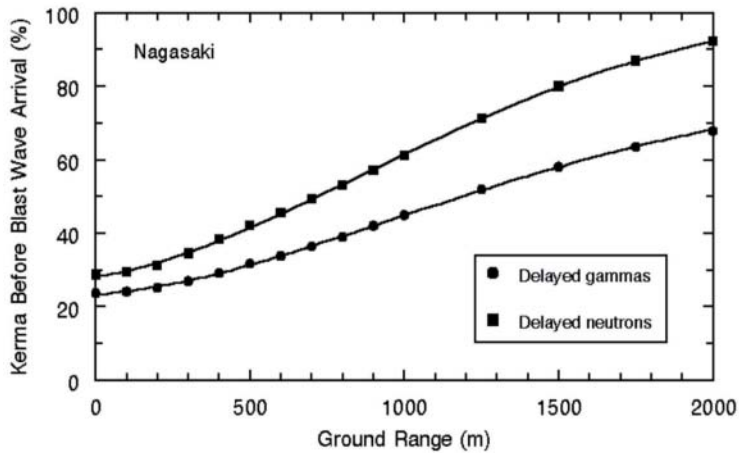


Figure 10. *Fraction of FIA tissue kerma that arrives before the blast wave at Nagasaki.*

Table 8. Curve-fit coefficients for fraction of FIA tissue kerma from delayed gamma rays and neutrons arriving before the blast wave at Nagasaki

Curve-fit coefficient	Delayed gamma rays	Delayed neutrons
a_0	2.342×10^{1}	2.825×10^{1}
a_1	5.700×10^{5}	1.230×10^{4}
a_2	2.676×10^{7}	3.716×10^{7}
a_3	-1.278×10^{10}	-1.874×10^{10}
a_4	1.800×10^{14}	2.538×10^{14}

tissue kerma that arrives before the blast wave that were obtained by fitting the data in Figure 10 to a polynomial of the form:

$$F = a_o + a_1R + a_2R^2 + a_3R^3 + a_4R^4 \quad (1)$$

where R is the ground range in meters for the factory worker of interest. A greater portion of the delayed neutron kerma arrives before the blast wave, because the fission products emit delayed neutrons more quickly than gamma rays and the delayed neutrons have a much smaller range in air than the delayed gamma rays.

The FIA tissue kerma at the position of a standing worker in a factory is calculated at a distance of 1 m above floor level. The FIA tissue kerma for a prone worker after the arrival of the blast wave is calculated at a distance of 15 cm above floor level. Thus, the FIA tissue kerma to a factory worker from gamma rays, K_G(in factory), and neutrons, K_N(in factory), are estimated to be:

$$K_G(\text{in factory}) = K_{PG}(\text{in factory at 1 m}) + F_{DG}\, K_{DG}(\text{in factory at 1 m}) + (1 - F_{DG})\, K_{DG}(\text{in factory at 15 cm}) \quad (2)$$

and

$$K_N(\text{in factory}) = K_{PN}(\text{in factory at 1 m}) + F_{DN}\, K_{DN}(\text{in factory at 1 m}) + (1 - F_{DN})\, K_{DN}(\text{in factory at 15 cm}) \quad (3)$$

where F_{DG} and F_{DN} are calculated using equation (1) and the curve fit coefficients in Table 8 for the delayed gamma rays and the delayed neutrons, respectively. The quantity $(1 - F_{DG})$ is the fraction of the FIA tissue kerma from delayed gamma rays that arrives after the blast wave, and the quantity $(1 - F_{DN})$ is the fraction of the FIA tissue kerma from delayed neutrons that arrives after the blast wave.

It is also of interest here to calculate the so-called transmission factors, TF, for the workers inside the factories. The factory transmission factors for the prompt gamma rays, TF_{PG}, and the prompt neutrons, TF_{PN}, are defined by the equations:

$$TF_{PG} = K_{PG}\,(\text{in factory at 1 m})/K_{PG}(\text{in open at 1 m}) \quad (4)$$

and

$$TF_{PN} = K_{PN}(\text{in factory at 1 m})/K_{PN}(\text{in open at 1 m}) \quad (5)$$

where the prompt gamma-ray and neutron kerma in the open and 1 m above ground are calculated at the same ground range as the other FIA tissue kerma for the worker in the factory. The factory transmission factors for the delayed gamma rays, TF_{DG}, and for the delayed neutrons, TF_{DN}, are defined by the equations:

$$TF_{DG} = [F_{DG}\, K_{DG}(\text{in factory at 1 m}) + (1 - F_{DG})\, K_{DG}(\text{in factory at 15 cm})]/\, K_{DG}(\text{in open at 1 m}) \quad (6)$$

and

$$TF_{DN} = [F_{DN}\, K_{DN}(\text{in factory at 1 m}) + (1 - F_{DN})\, K_{DN}(\text{in factory at 15 cm})]/\, K_{DN}(\text{in open at 1 m}) \quad (7)$$

where the delayed gamma-ray and neutron kerma in the open and 1 m above ground are also calculated at the same ground ranges as the other FIA tissue kerma for the worker in the factory. The same approach as outlined above can also be used to calculate the organ doses for the factory workers, taking into account the fraction of the organ dose from delayed gamma rays and delayed neutrons that are delivered to a worker before the arrival of the blast wave.

Results of Detailed Calculations

Forty workers at different locations in Building 22 were analyzed. The locations were chosen to obtain a representative map of the kerma and transmission factors. Data were obtained for workers in open areas that were not shielded by workbenches or machinery and those behind workbenches or working at drill presses and lathes. Figure 11 shows the as-modeled locations of workers in the building at the time the weapon detonated, drawn to scale according to the actual factory coordinates and equipment dimensions used as input by ORNL. These data were taken by ORNL from building floor plans annotated with survivor locations provided by the RERF. To keep the problem size in a practical range, only objects directly affecting the forty modeled

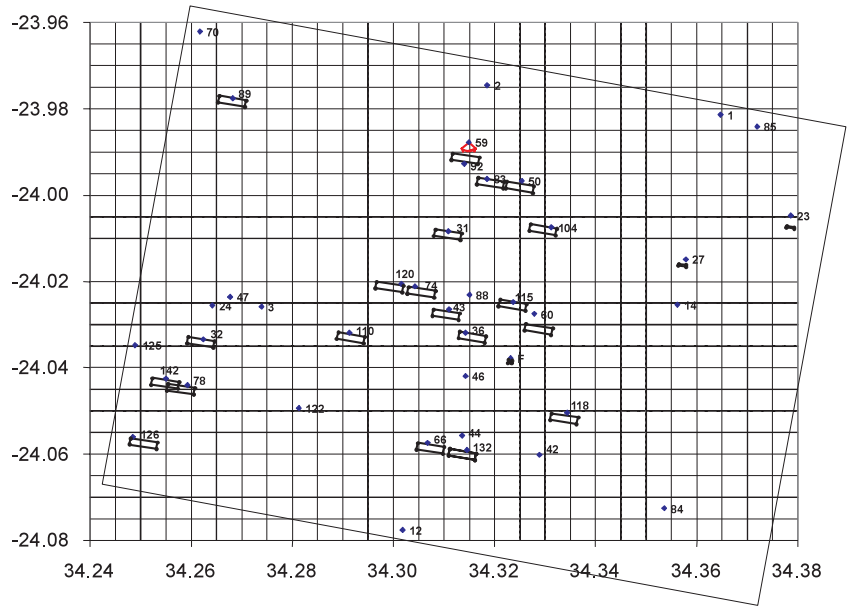


Figure 11. *Worker and equipment positions as used in the ORNL MASH calculations. Grid squares are 5 yards. A 90° sector of 2-m radius, centered on the direction to the hypocenter, is drawn for position 59, for illustration. Position number 115, as shown here, is referred to as position number 113 in some parts of the discussion because of difficulty in reading the original drawing from which these positions were taken.*

positions were included in the MASH calculation—the calculation did not contain all of the benches and other objects shown in the actual drawings. The locations of the workbenches or machinery affecting the kerma to survivors are shown. Figure 12 shows the factory worker locations in the building. If a worker was in front of a workbench or piece of machinery, the worker was considered to be in the open, since it did not provide effective shielding. If a worker was close to or behind a workbench or piece of machinery, he was considered to be shielded by the object, since the exact location of these workers with respect to it could not be precisely determined from available information. The shielding of each worker is noted by the symbol type.

The results of this study are presented in Tables 9-12. Table 9 summarizes the locations and corresponding FIA kerma components for each factory worker. Each worker is identified by a number on the factory map. The survivor's ground distance was determined by his location and the hypocenter location on the U.S. Army map. The distance from the survivor to the front wall was determined from the factory map. Shielding categories are given for each worker as either close to (close) or far from (far) the front wall, and as shielded by workbench (bench) or in the open (open). The fraction of the delayed kerma that arrives before the blast wave is given for the neutron and gamma-ray kerma. This is used in proportioning the delayed kerma. The kerma is calculated for six components: the neutron and gamma-ray kerma are each broken into the prompt, delayed before, and delayed after the blast wave passes the factory. The worker's kerma is calculated at 1-m height above the floor until the blast wave passes. After that time the kerma

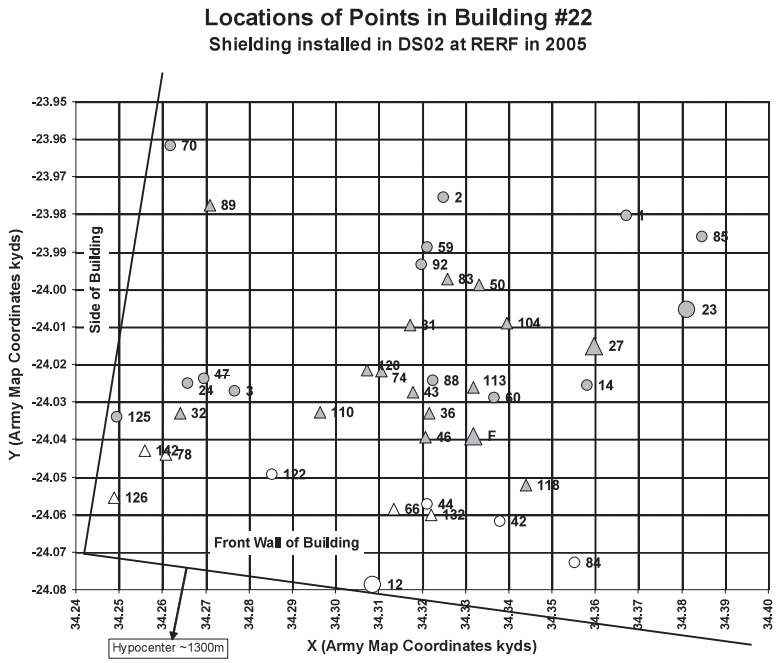


Figure 12. *Locations of workers in Building 22 and DS02 shielding category indicated (triangles—behind workbench; circles—in open; large triangles behind lathe or press; or large circles—in open by lathe or press; symbols with white centers are close to front wall; grey centers are far from front wall).*

Next Page