DS02R1: Improvements to RERF's Dose Estimates for the Atomic Bomb Survivors

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RERF

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Topics

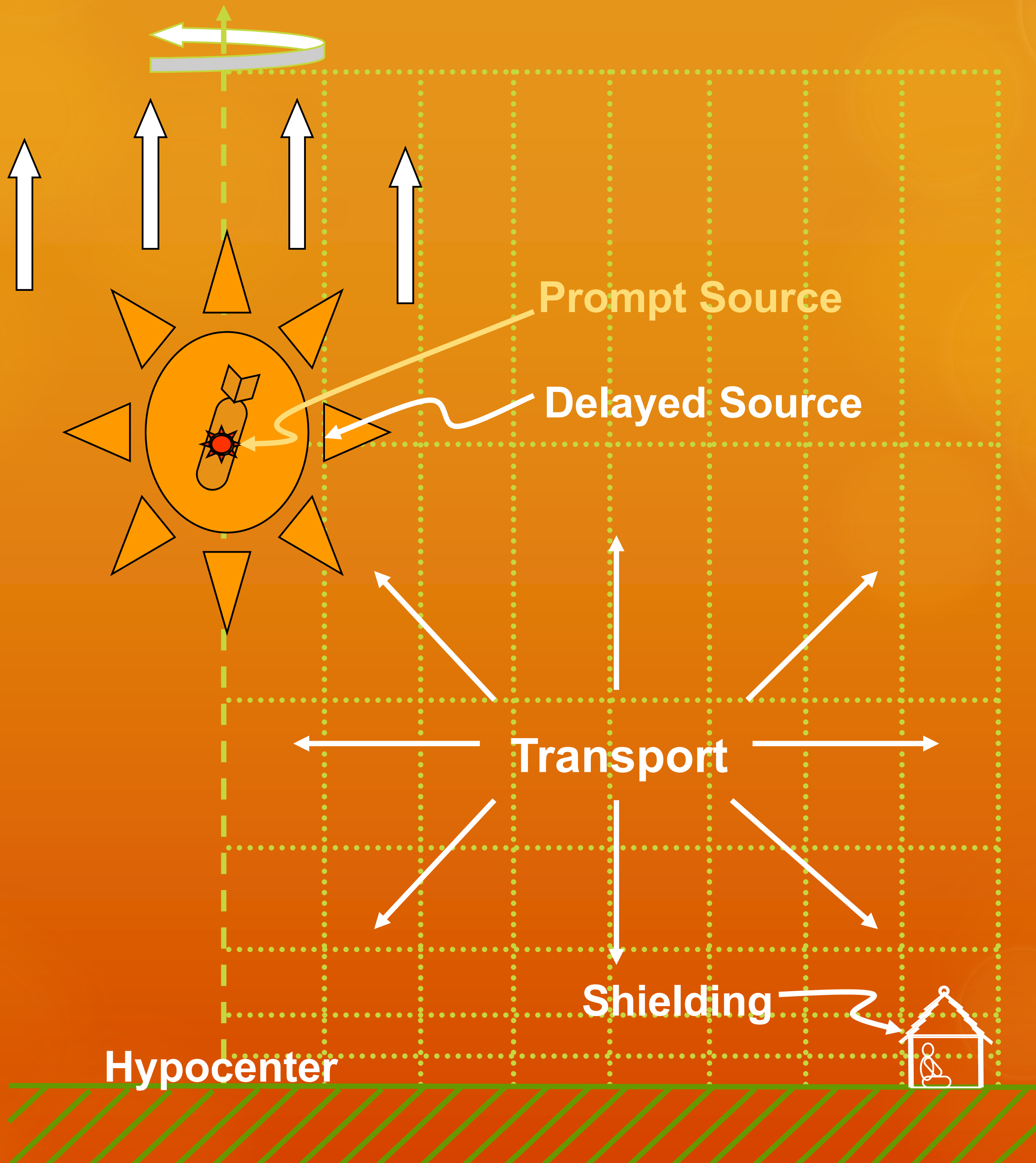
- ABCC/RERF Dosimetry Systems
- DS02R1 – Improvements
- Changes in Dose Estimates
  - Effect on Risk Estimates

Dosimetry Systems – What and Why

- Doses had to be *calculated* based on survivors' location and shielding
- No data from personal monitors
- Biodosimetric data few and very noisy

Doses calculation based on survivors' location and shielding

- Practical because
  - Source term and location-specific radiation with no shielding could be accurately calculated
  - Most survivors' shielding had common features that made modeling feasible



Prompt Source
Delayed Source
Transport
Shielding
Hypocenter

Radiation vs. Location

- Research by many investigators over many years
- → Precise estimates
  - Of "*bomb parameters*"
    - Used in calcuations

Bomb Parameters

- Location of hypocenter
  - Shadow lines etched on stone surfaces by heat from fireball
- Bomb yield
  - Calculations
  - Measurements of exposed environmental samples
- Height of burst
  - Same methods as above

Fluence

- Number of neutrons or γ-rays per unit cross-sectional area (e.g., m^{-2})
- Specific to a category of energy and direction

Fluences ↔ Modular nature of DS02

- DS86 and DS02 calculate *fluences*
  - Emanating from bomb (*source term*) –
    - calculated from bomb physics
    - verified empirically by replica devices (prompt), other sources, nuclear weapons tests
  - At ground level after scattering and attenuation in the air-over-flat-ground environment (→ *free-in-air kerma*)
    - Major transport calc's were 2D finite-elements ("discrete ordinates" spatial mesh) method assuming cylindrical symmetry
    - Large 3D forward Monte Carlo calculations were also done for DS02

Fluences ↔ Modular nature of DS02

- DS86 and DS02 calculate *fluences*
  - After successive levels of shielding (→ *shielded kerma*)
    - Terrain – terrain model uses "grazing angles" to horizon in 5 azimuthal directions
    - Structures (house, etc.) – model house cluster
  - After self-shielding by overlying tissues of survivor's body
    - → fluences traversing an organ of interest
      - Converted to *dose*
    - DS02 uses the old stylized phantoms of DS86

DS02 Models

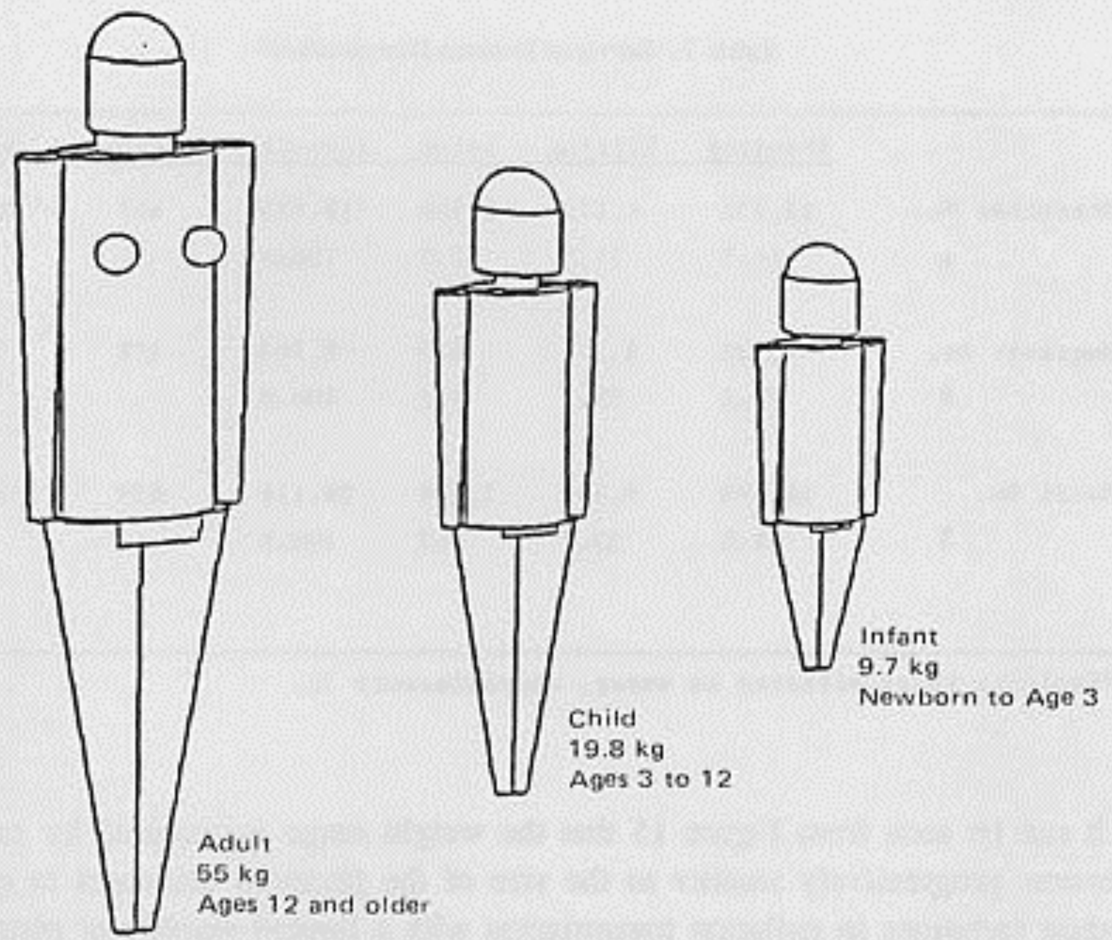
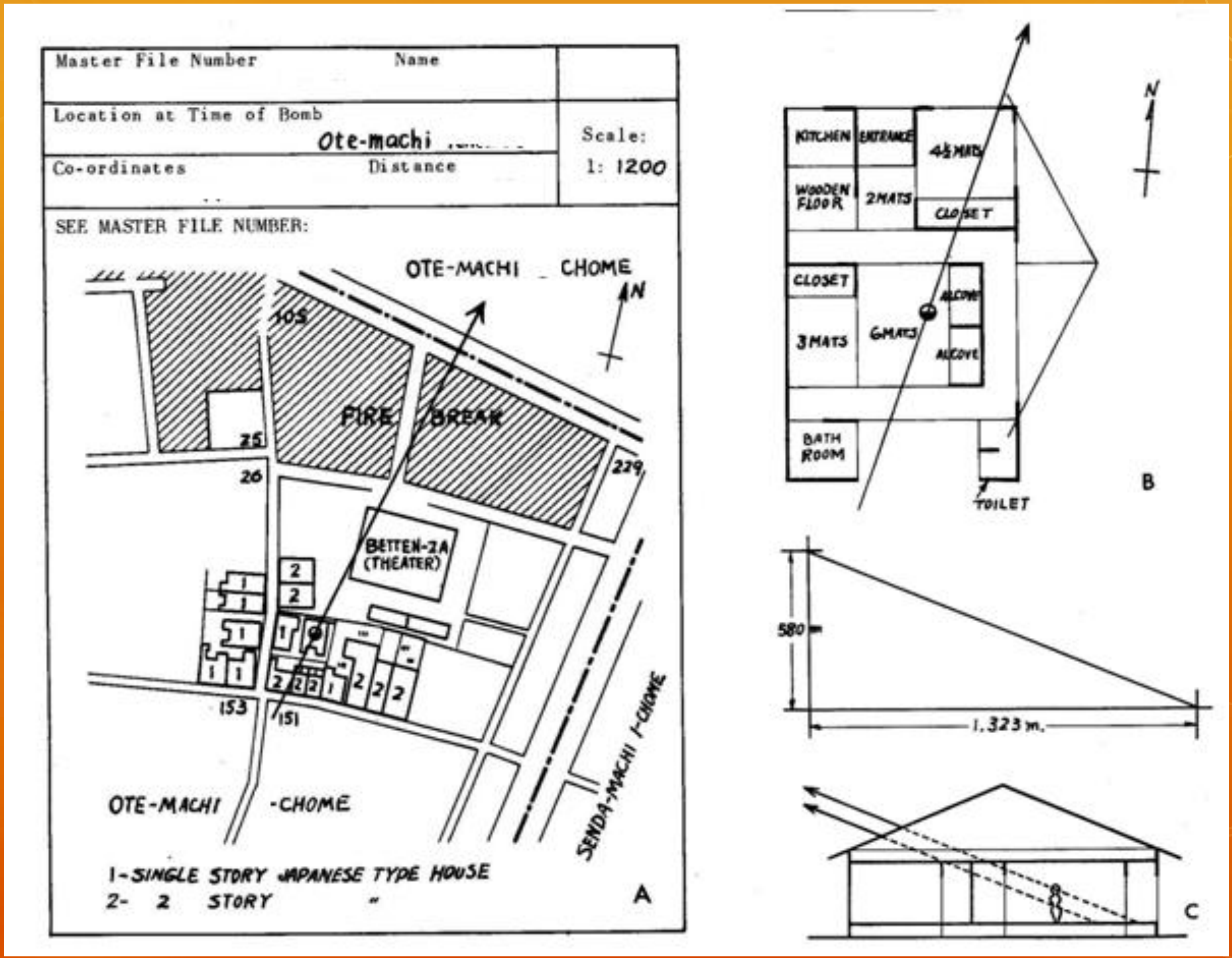


Figure 14. External configuration of three phantoms representing adult, child, and infant survivors

Survivor Location and Shielding

- Huge effort to obtain data on location and shielding conditions for individual survivors
- Many surveys over the years in 1950s and 1960s
- Most important: shielding histories with drawings of house etc.
  - Stopped in 1963 when complete to 1600 m in Hiroshima and 2000 m in Nagasaki
    - 42% complete between 1600 and 2000 m in Hiroshima

Shielding Histories



DS02R1

Improved Input Data

Original Source Documents

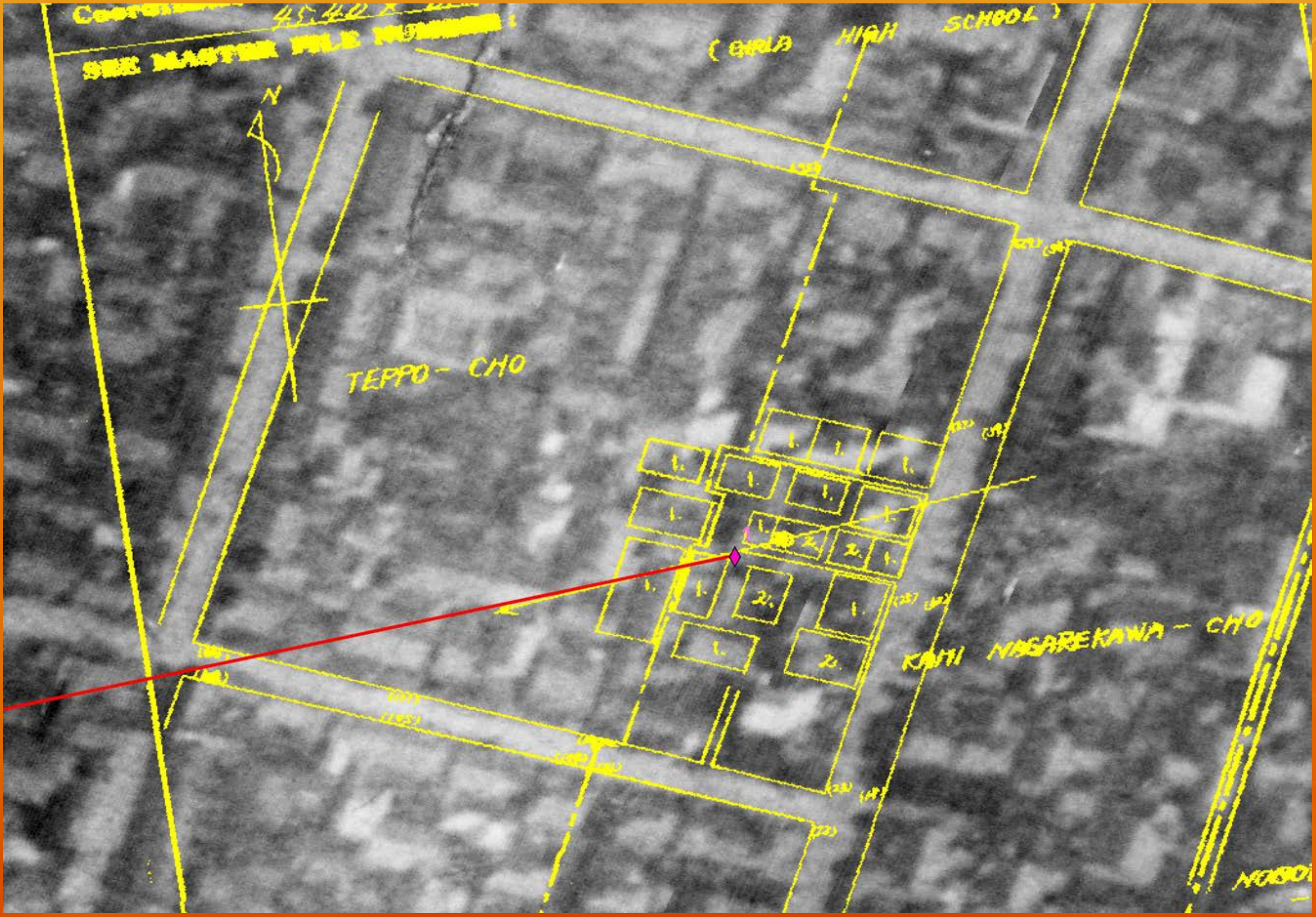
- Data re location and shielding at time of bombing were originally collected from 1949-1963 by interviews using various forms
- For DS02R1, all data were newly vetted, collated, and prioritized based on reliability
  - Used most reliable datum for each survivor
- Various errors were corrected
- Survivors without shielding histories located by coordinates on 1945 U.S. Army maps
  - Digits for 10s of yards (1 yard = 9.14 m) previously truncated from U.S. Army map coordinates in some cases were restored

Precise Location of Neighborhood Diagrams from Shielding Histories

- Create an orthophotographic mosaic of the pre-bombing aerial photographs of each city
- Align new city maps with orthophotographic mosaics
- Locate each neighborhood diagram and align with the orthophotographic mosaic using street corners etc. as control points

Orthophotographic Mosaic of Hiroshima Made from Pre-bombing Aerial Photographs

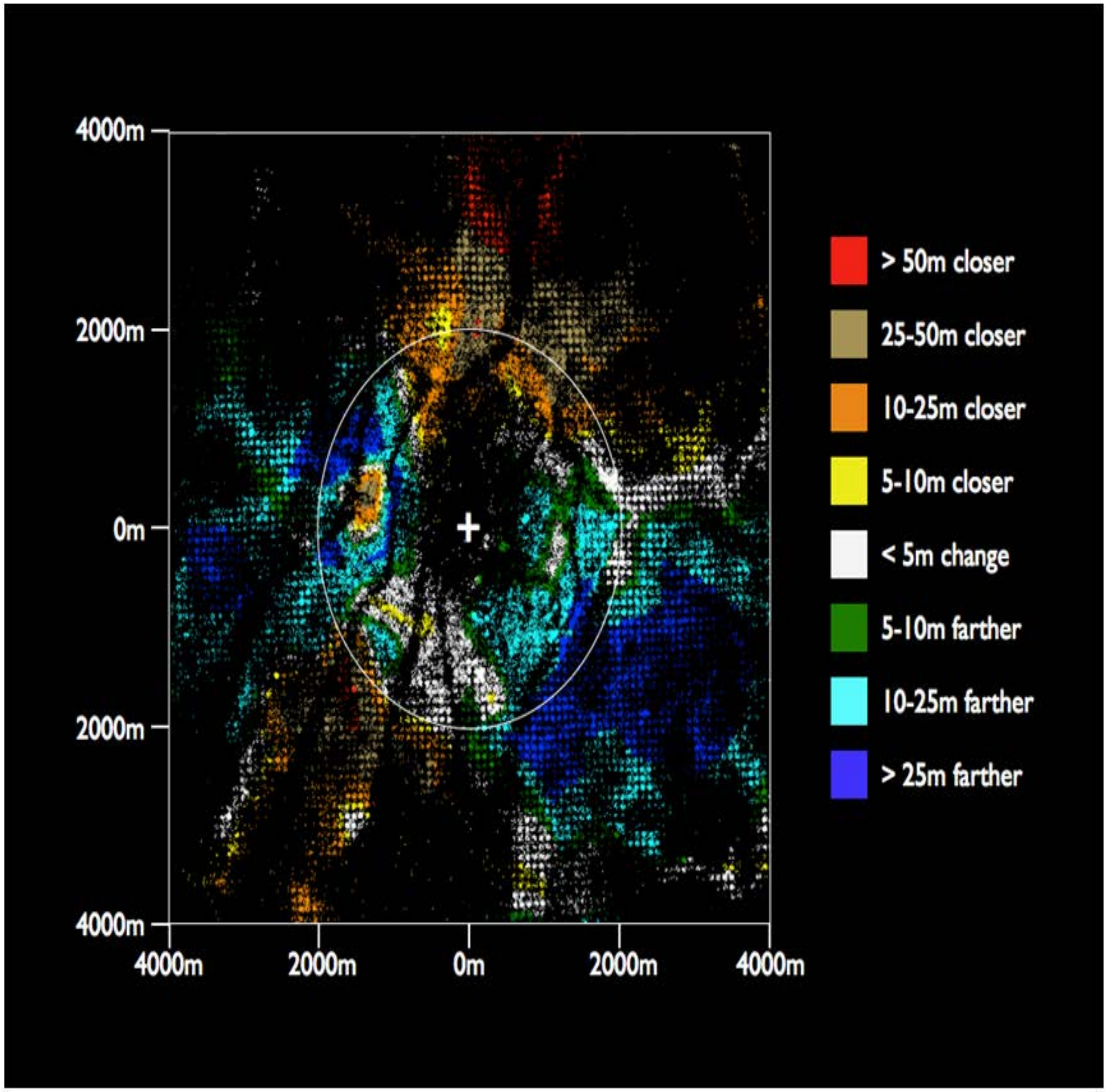
Drawings in Shielding Histories



Correction of Distortions in U.S. Army Maps

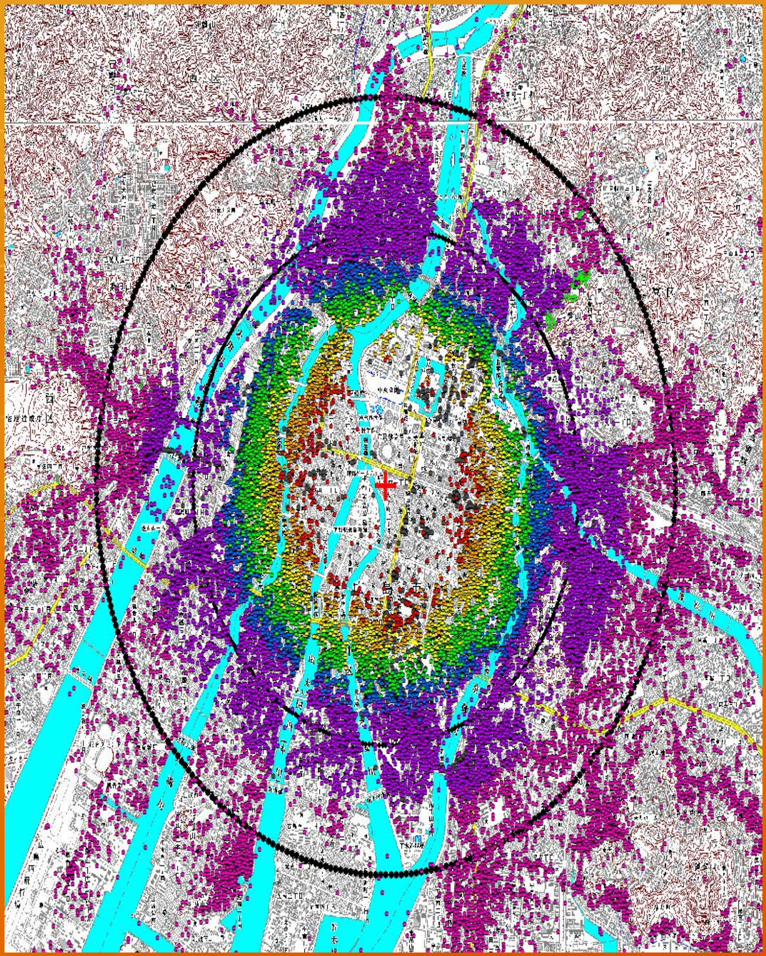
- Pick control points consisting of road intersections, bridges, etc.
  - Uniquely identifiable and unmoved on both orthophotographic mosaic and U.S. Army map
- Align map to orthophotographic mosaic using a flexible "rubber sheeting" method
  - Stretch or compress map differently in different areas

Changes in Distance Due to Correction of Distortions in U.S. Army Map of Hiroshima

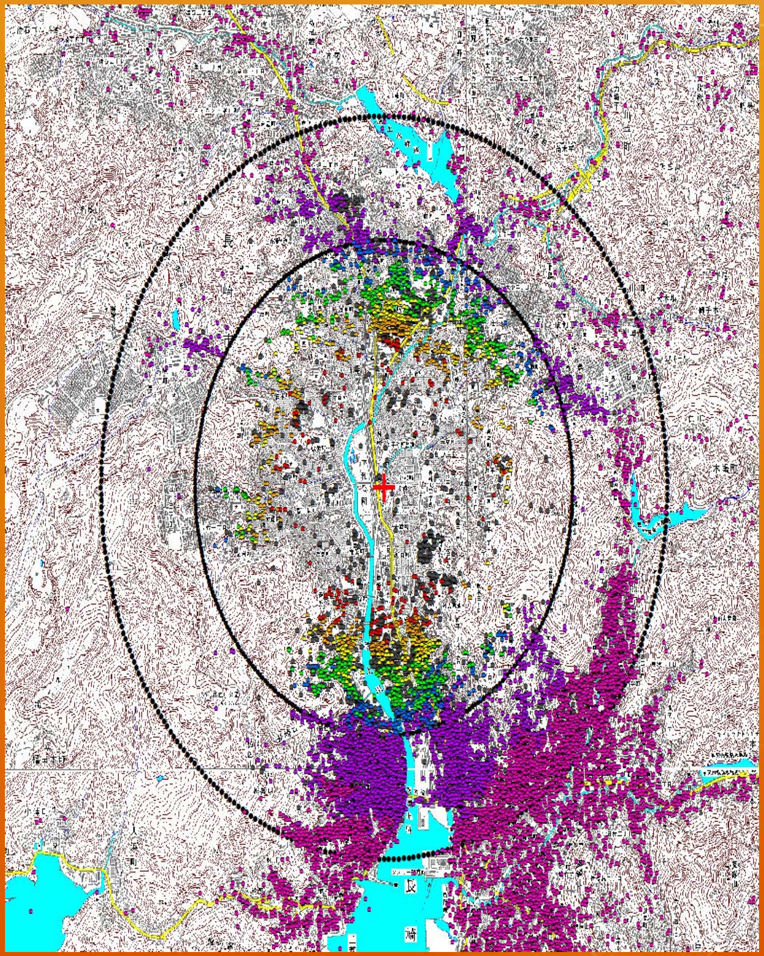


Survivor Locations on Contemporary Maps

Hiroshima



Nagasaki



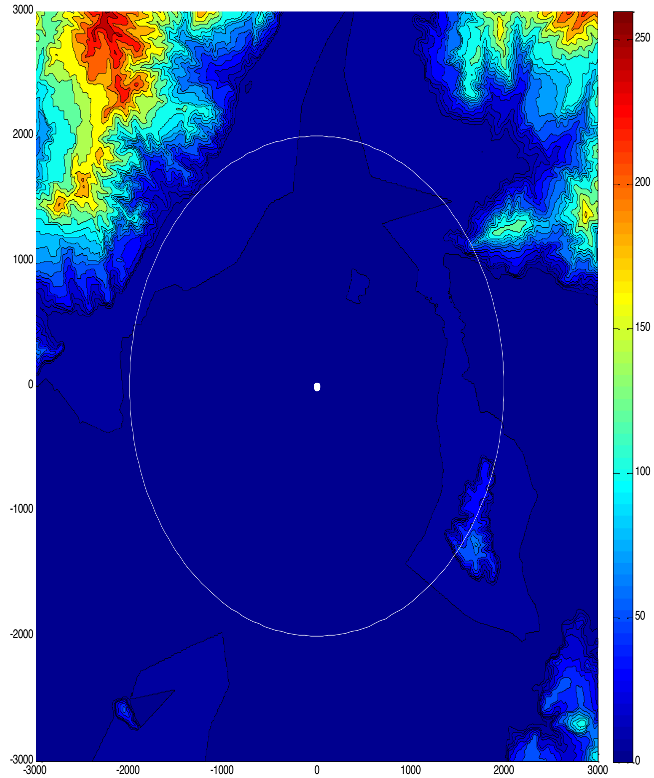
Background: Digital Map 25000, Geographical Survey Institute of Japan, 2002. Circles of black dots at 2 and 3 km from hypocenter. Color key, in order of drawing, starting with bottom layer: dark gray = unknown dose, pink < 5 mGy, purple 5 to 100, blue 100 to 200, green 200 to 500, yellow 500 to 1,000, orange 1,000 to 2,000, red > 2,000.

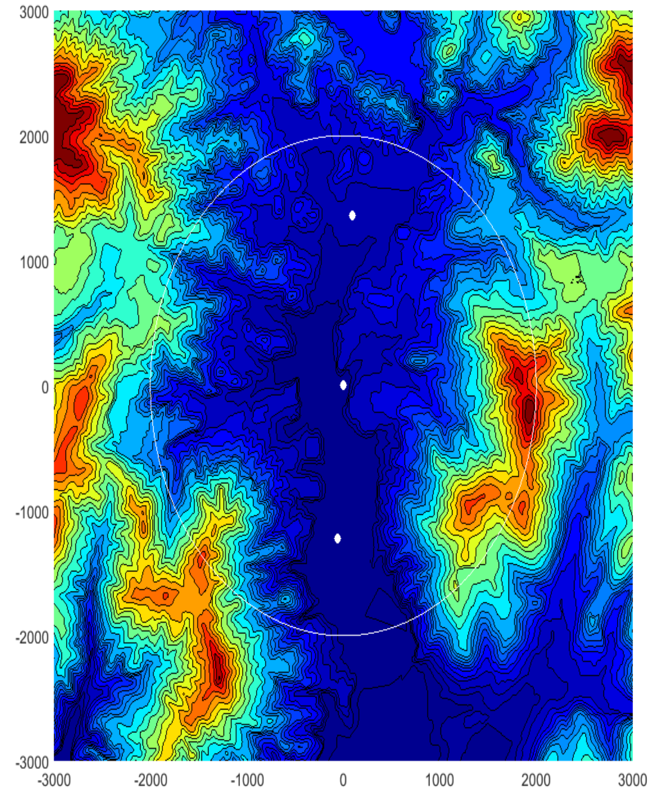
Revised and Greatly Expanded Terrain Shielding Input Data

- Obtain new "grazing angles" for ALL survivors
  - To use as input data for terrain shielding
  - Using survivor's new location and digital terrain elevation data on a ~10-m grid
- Extensive checking vs. 1966 data for 315 Nagasaki "globe terrain" cases
- Correct angles for survivor's elevation above sea level

Digital Terrain Data in the Two Cities

Hiroshima / Nagasaki

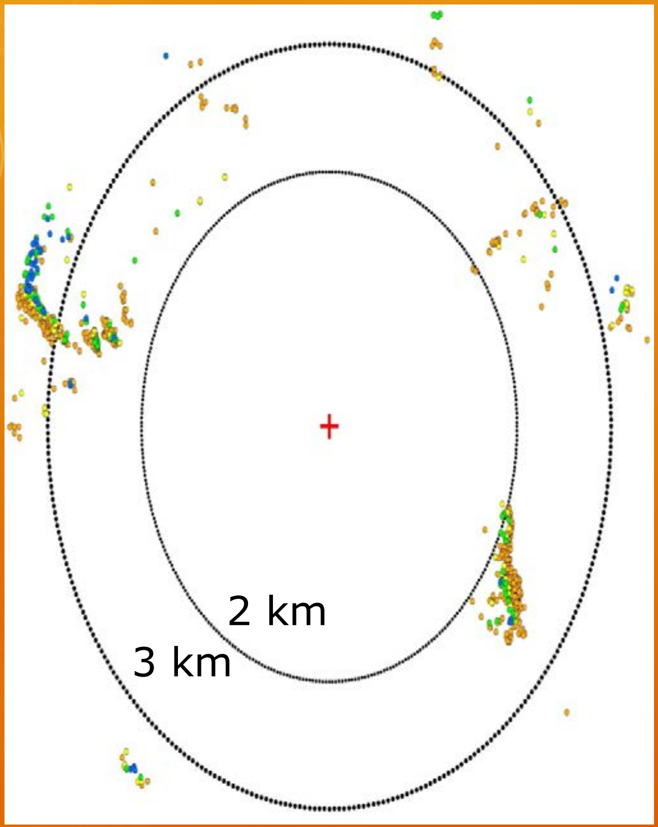




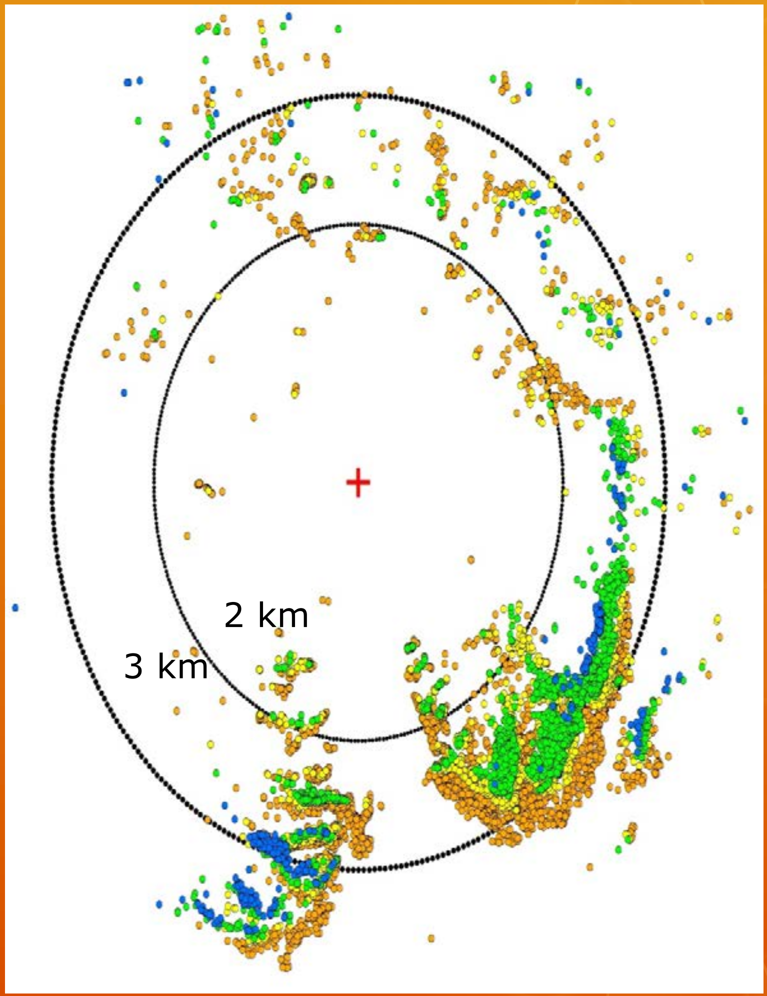
Contours shown are at elevations of 0, 5, 10, 15, 20, 30, …, 90, 100, 120, …, 320, 340 m (by 5 m intervals to 20 m, 10 m intervals to 100 m, 20 m intervals to 340 m). The white circle has radius 2 km.

Locations of Substantially Terrain-Shielded Survivors

Hiroshima



Nagasaki

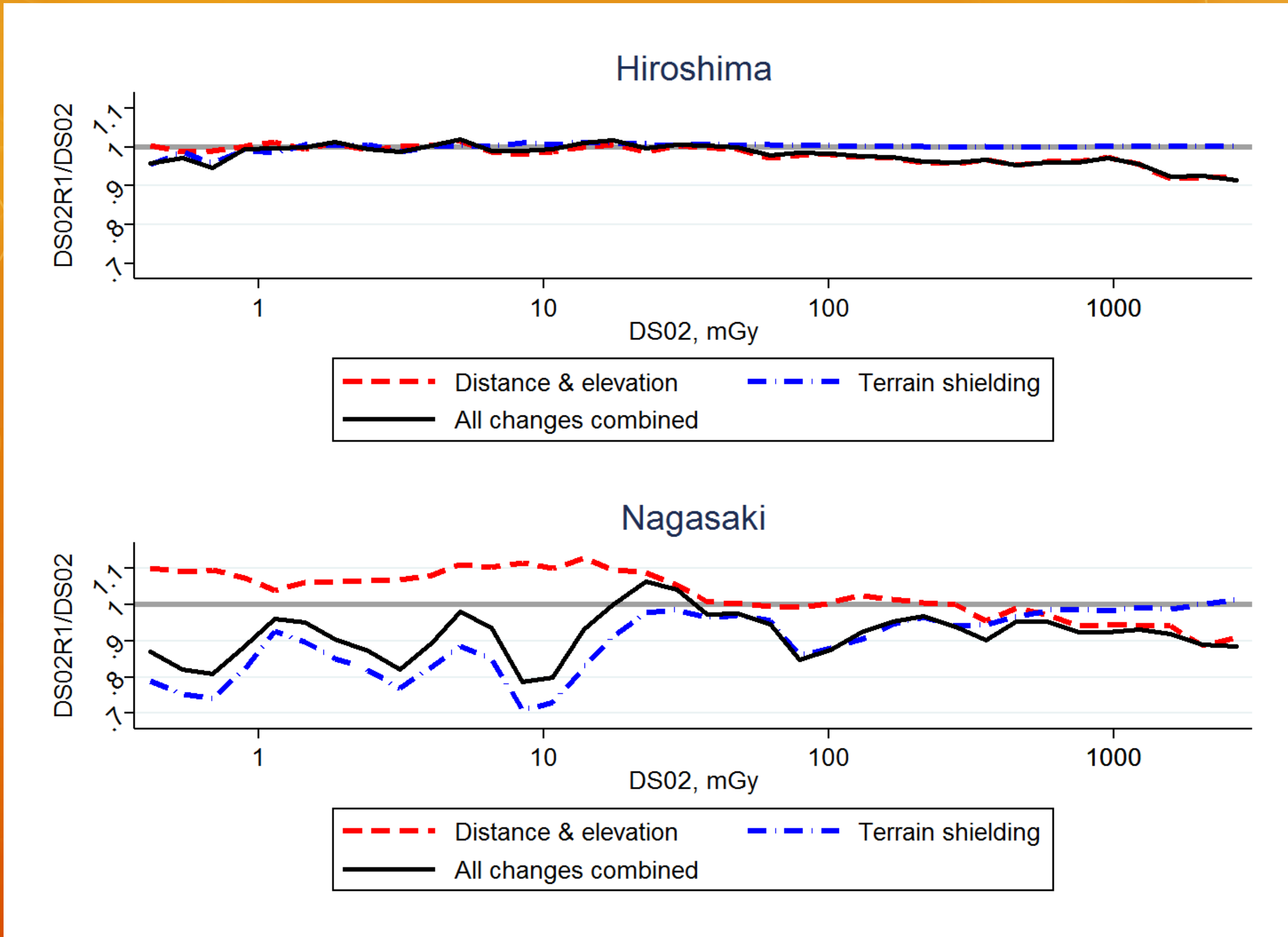


Key: terrain γ-ray transmission factor
<0.3 0.3 – 0.5 0.5 – 0.7 0.7 –0.9

Other Changes

- Improved method of truncating high dose estimates to 4 gray total dose
  - More appropriate neutron/gamma-ray ratio
- Fixed error in DS02's calculation of combined house and terrain shielding

Systematic Changes:DS02R1 vs. DS02



Effect on Risk Estimates: Cancer Mortality

	Report 14 Public Data -- DS02 (orig) *			
	Full Dose Range		<2 Gy**	
	Male	Female	Male	Female
Linear	0.25 (0.06, 0.47)	0.47 (0.24, 0.73)	0.06 (-0.18, 0.32)	0.35 (0.06, 0.67)
Quadratic	0.013 (-0.08, 0.11)	0.062 (-0.07, 0.20)	0.20 (0.01, 0.39)	0.17 (-0.06, 0.41)
Curvature	0.05	0.13	3.2	0.50
p-value (curvature)	p>0.50	p=0.36	p=0.03	p=0.14
Effect Modification				
Age at exposure (per decade increase)	-29%		-29%	
Attained age (power)***	-0.85		-0.92%	
Deviance	18298.1		18289.3	
df	53145		53141	

0.34417

	Report 14 Data -- rerun with DS02R1***			
	Full Dose Range		<2 Gy**	
	Male	Female	Male	Female
Linear	0.23 (0.04, 0.44)	0.48 (0.24, 0.75)	0.11 (-0.12, 0.37)	0.27 (0, 0.57)
Quadratic	0.03 (-0.07, 0.13)	0.06 (-0.07, 0.21)	0.13 (-0.05, 0.32)	0.27 (0.05, 0.50)
Curvature	0.12	0.13	1.14	1.01
p-value (curvature)	p>0.50	p=0.37	p=0.15	p=0.02
Effect Modification				
Age at exposure (per decade increase)	-31%		-32%	
Attained age (power)	-0.83		-0.89	
Deviance	18321.6		18311.6	
df	54426		54422	

0.33647

DS02R1 Summary

- Several major improvements in dosimetry input data
- Systematic changes in dose estimates mainly due to
  - method of truncating high doses to 4 Gy (high doses) and
  - addition of previously-ignored terrain shielding (low doses)

DS02R1 Summary

- Random changes believed to → overall reduction of random error in DS02 doses
- Changes in risk estimates
  - Small for major risk parameters
    - e.g., ERR for an overall linear dose-response
  - But sometimes more substantial for more-restricted parameters
    - e.g., sex-specific curvature in ERR on doses < 2 Gy

Reference:
Health Physics 112(1), 56-97 (2017)

- DS02R1: Improvements to Atomic Bomb Survivors' Input Data and Implementation of Dosimetry System 2002 (DS02) and Resulting Changes in Estimated Doses

- Cullings HM[1], Grant EJ[2], Egbert SD[6], Watanabe T[2], Oda T[2], Nakamura F[2], Yamashita T[2], Fuchi H[2], Funamoto S[1], Marumo K[3], Sakata R[2], Kodama Y[4], Ozasa K[2], Kodama K[5]

- Departments of [1]Statistics, [2]Epidemiology, [3]Information Technology, [4]Biosample Center, and [5]Chief Scientist, RERF; [6]LEIDOS Corporation, San Diego, California

Organ Dosimetry

New phantoms and calculations

Key points

- DS02 uses an organ dose module inherited from DS86, created in the early 1980s
- The organ dose module has substantial deficiencies
- Due to the modular nature of DS02, a new organ dose module could be created to replace the current module without changing other parts of DS02

DS86/DS02 organ dose module

- Simple models of the human body
  - e.g., spheres, cylinders, truncated cones, etc.
- 3 models: infant (0 to 2 yrs), child (3 to 11 yrs), adult (12+ yrs)
- No pregnant woman + fetus
  - Current expedient: uterine dose of non-pregnant woman
- Calculates 15 organs
  - Which were thought to be of concern ~ 1983
    - i.e., as sites of cancer
  - Many other organs are contained in contemporary phantoms, both stylized and voxel types

DS86/DS02 Phantoms

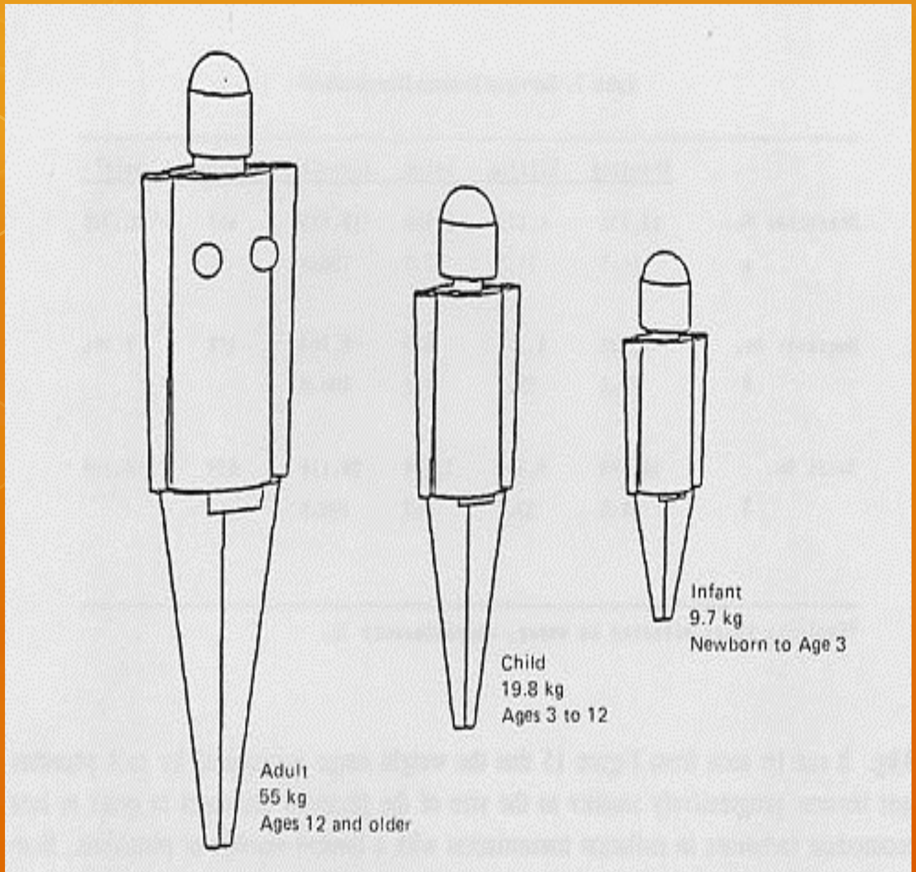


Figure 14. External configuration of three phantoms representing adult, child, and infant survivors

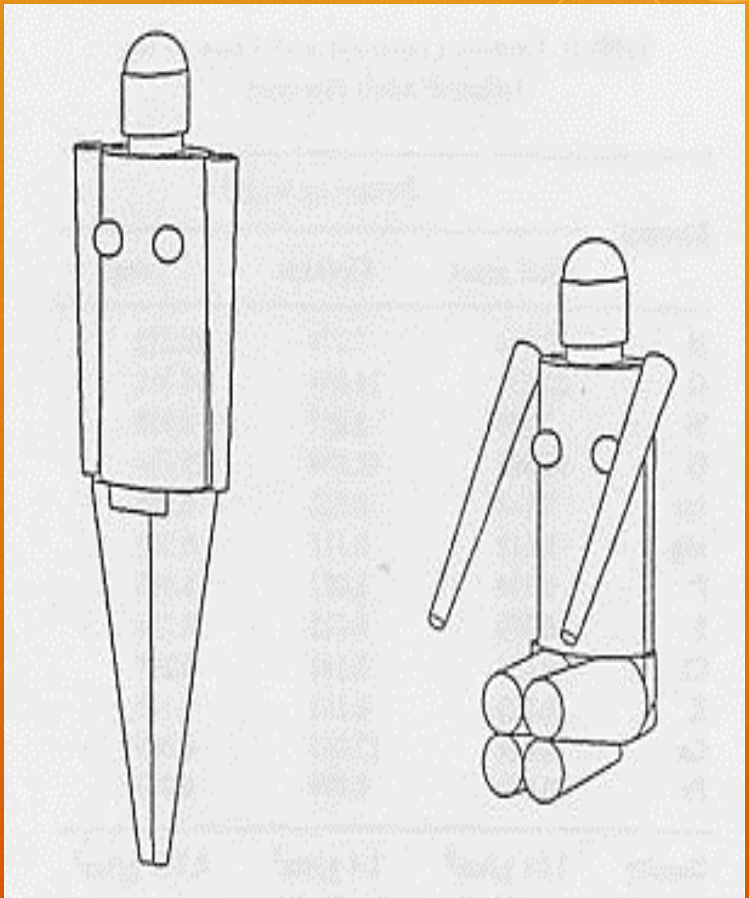
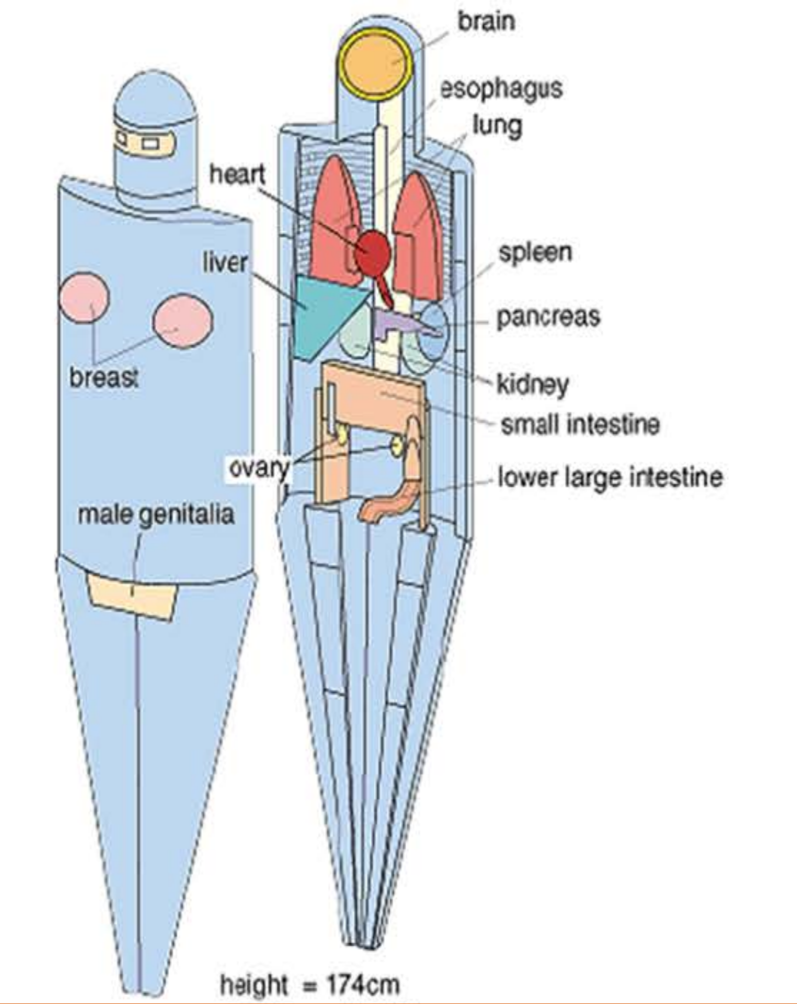


Figure 1. The Japanese adult phantom

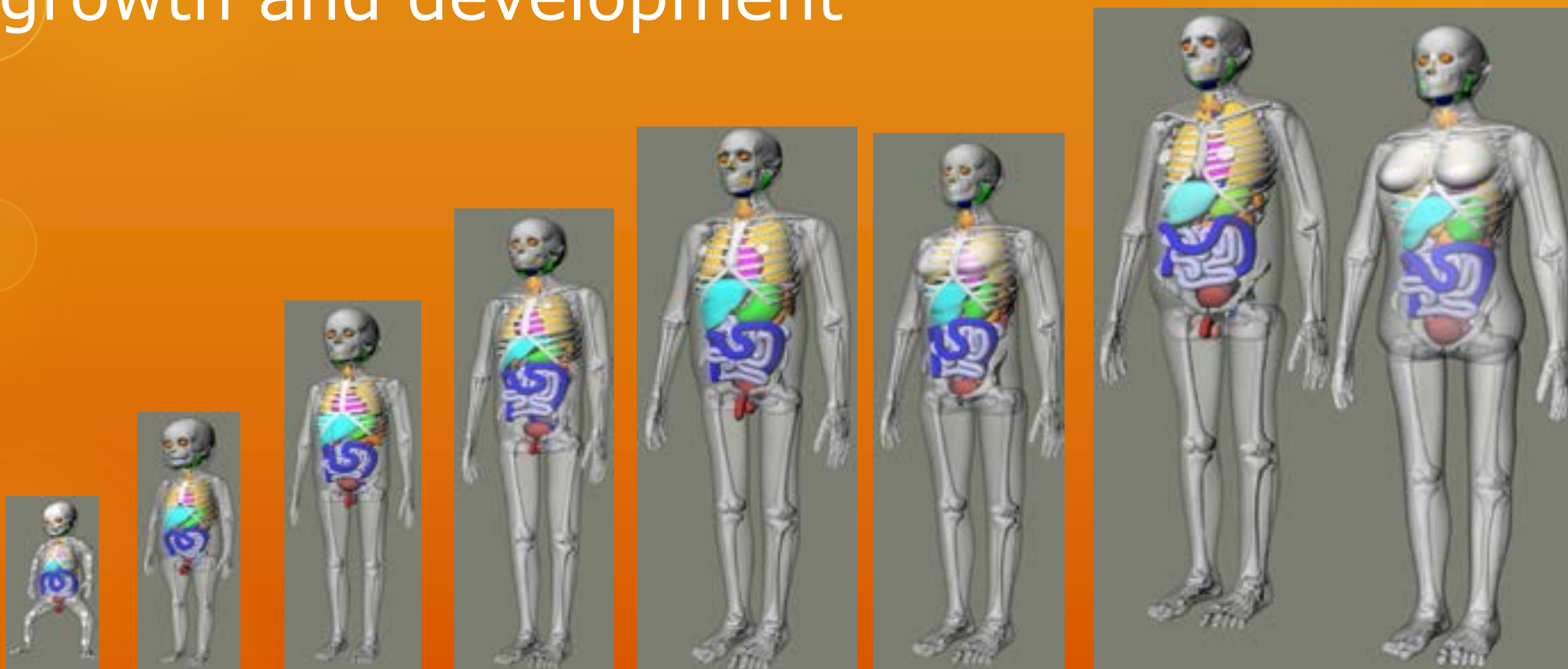
A Contemporary Stylized* Phantom



*surfaces described by mathematical equations

A Contemporary Pediatric Series

e.g., ~ 5 phantoms to capture changes in body size and anatomical proportions throughout growth and development

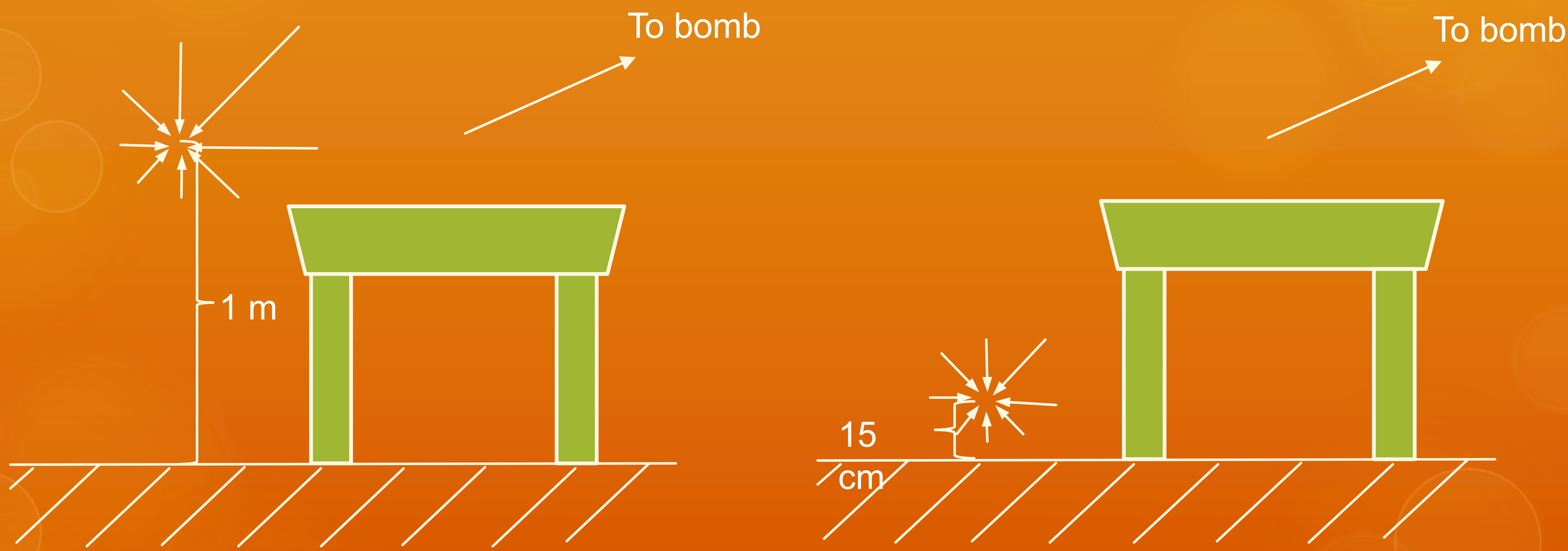


University of Florida series, courtesy of Wes Bolch

The DS86/DS02 Organ Dose Module

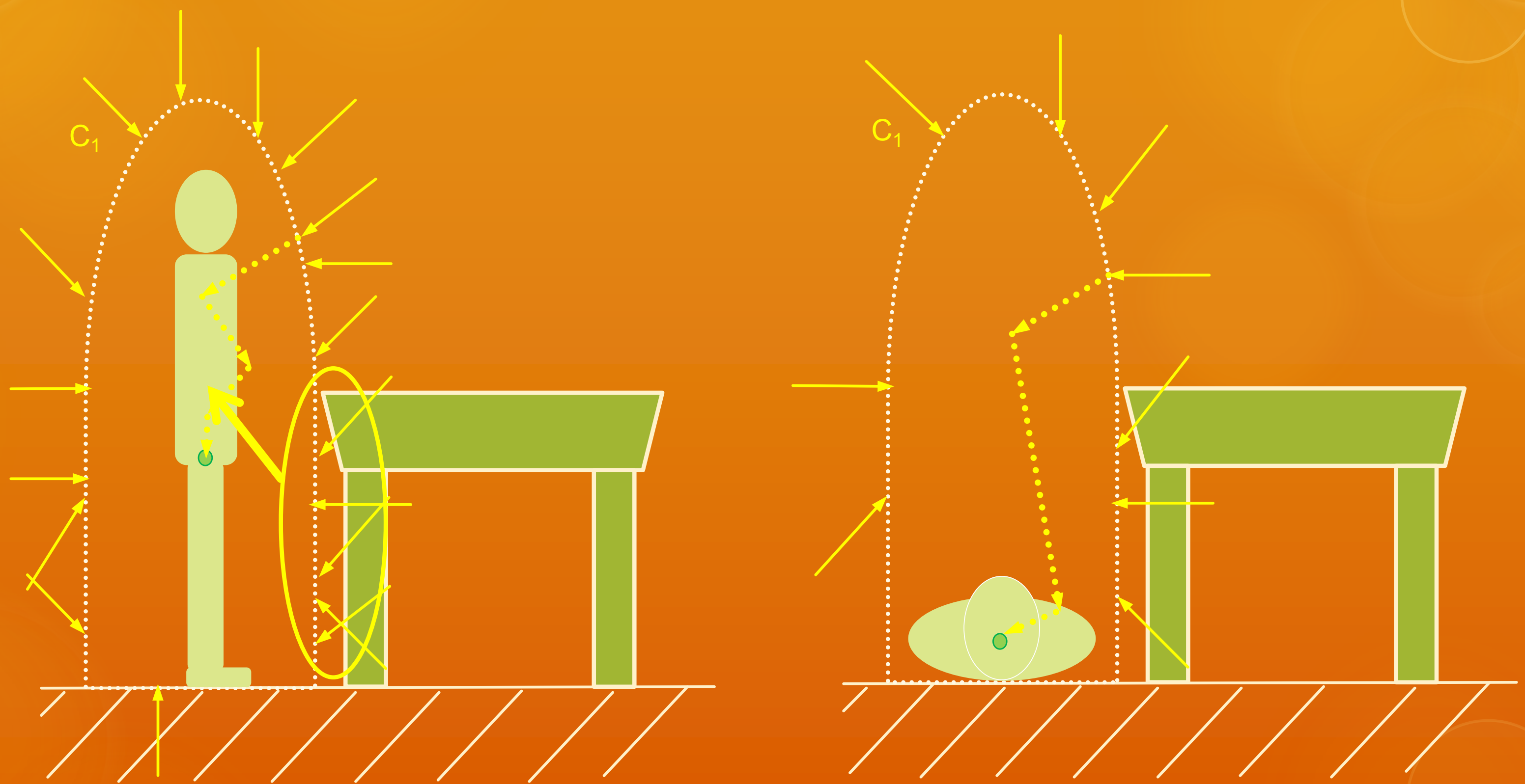
- Does not include many tissues and organs related to radiation effects recognized after early 1980s
  - e.g., heart, kidney, etc.
- Does not have a way to calculate partial body shielding for factory workers behind benches or machine tools
  - Couples the fluences at 1 m or 15 cm above ground (standing/sitting vs. lying down) to the body phantom
    - Entire body therefore receives the same shielding, no partial-body shielding calculable
  - Need a combined phantom with body and bench/tool both inside coupling surface
    - And related calculations

Partial-Body Shielding of Factory Workers



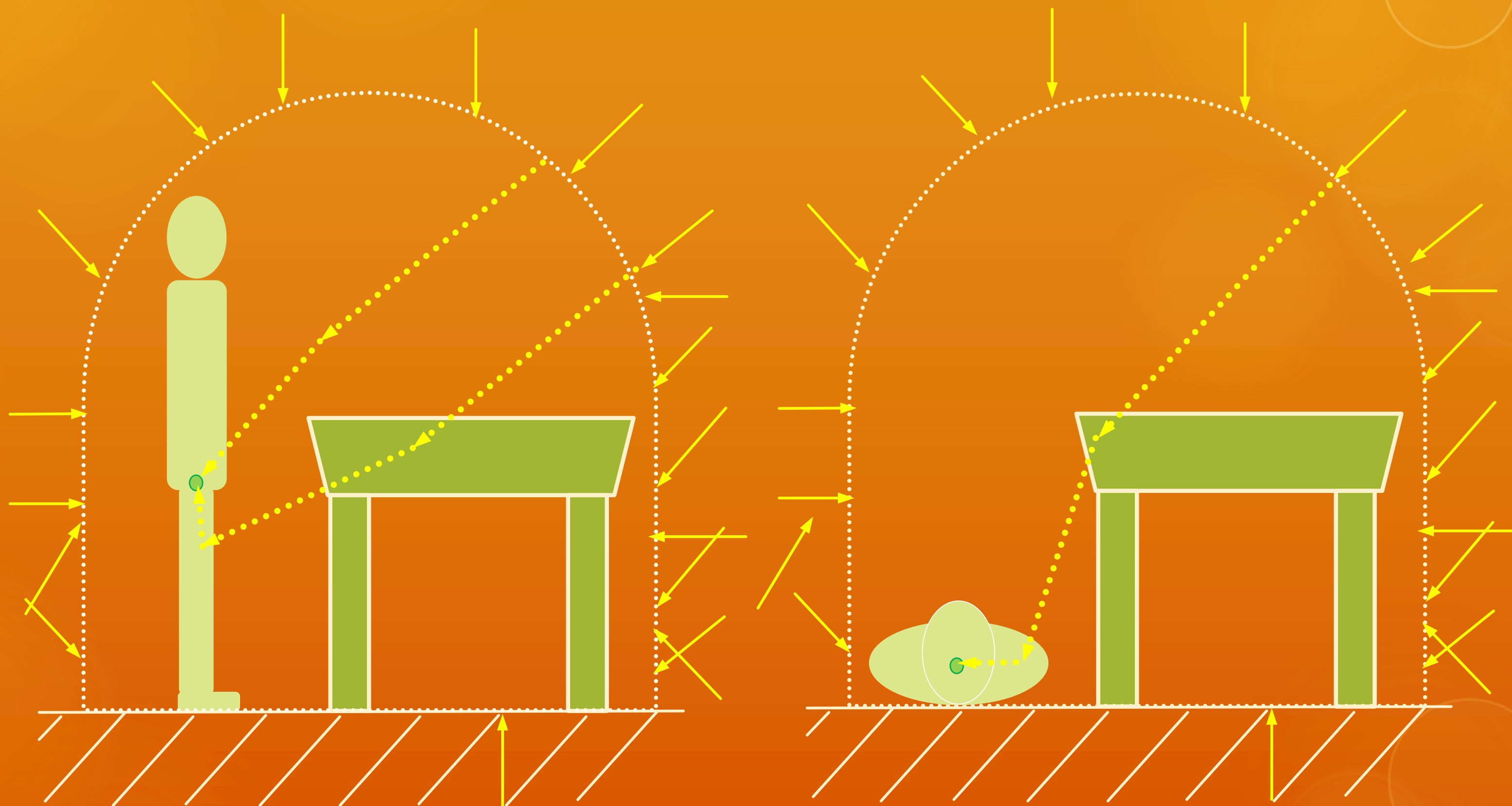
DS02's available calculated fluences in factory model at a location behind a bench

Partial-Body Shielding of Factory Workers



Current DS02 calculation: before blast wave (left) and after (right).

Partial-Body Shielding of Factory Workers



Planned type of model: before blast wave (left) and after (right).

DS86/DS02 Organs

bladder	breast	brain	colon	eye (lens)
liver	lung	ovaries	pancreas	bone marrow
skeleton	stomach	testes	thyroid	uterus

- Not included: heart, kidneys, major blood vessels, teeth (for ESR), other possible organs of interest
- Skin dose usually taken as = shielded kerma, a questionable assumption
- Correctness of DS86 calculation for lens of eye is questionable

Body self-shielding for γ-rays is modest

- Due to high overall energy of photons
- But related dose reductions are not trivial…
- Effects of survivor orientation are calculated but input data are questionable
  - Rotationally-averaged values can be used

Table 75. Transmission Factors Prompt Gamma-ray Kerma in All Organs of Adult (55 kg), Child (19.8 kg), and Infant (9.7 kg) Japanese Phantoms, Relative to the Free Field, Nagasaki

Organ	Transmission (Organ Kerma[a] : Free-Field Kerma[a])			
	BEIR-80[b]	Adult[c]	Child[c]	Infant[c]
Active Marrow	0.56	0.780	0.817	0.971
Bladder	0.45	0.850	0.913	0.865
Bone	-	0.823	0.879	0.836
Brain	-	0.795	0.847	0.840
Breasts	0.80	0.937	0.887	1.010
Eyes	-	0.944	1.018	0.975
Fetus/Uterus	0.42	0.819	0.779	0.910
Intestinal Tract	0.40	0.823	0.903	0.837
Kidney	0.52	-	-	-
Liver	0.47	0.897	0.921	0.926
Lungs	0.50	0.796	0.925	0.926
Ovaries	0.40	0.752	0.868	0.934
Pancreas	0.40	0.809	0.825	0.876
Stomach	0.47	0.869	0.922	0.968
Testes	-	1.044	0.983	0.896
Thyroid	0.70	1.063	0.983	0.972

[a] Soft tissue Kerma.

[b] Table V-6, page 162, The Effects on Populations of Exposure to Low Levels of Ionizing Radiation: 1980, National Academy Press, Washington, D.C., 1980. Isotropically incident radiation on adult phantom.

[c] Transmission calculated using reduced (6000 history) DS86 organ data base at 1500 meters from hypocenter, standing phantom, facing hypocenter.

Body self-shielding for neutrons IS PRONOUNCED

- Due to frequent mechanical collisions with protons (nuclei of H atoms)

Table 74. Transmission Factors for Prompt Neutron Kerma in All Organs of Adult (55 kg), Child (19.8 kg), and Infant (9.7 kg) Japanese Phantoms, Relative to the Free Field, Nagasaki

Organ	Transmission (Organ Kerma[a] ÷ Free-Field Kerma[a])			
	BEIR-80[b]	Adult[c]	Child[c]	Infant[c]
Active Marrow	0.28	0.338	0.433	0.556
Bladder	0.18	0.302	0.377	0.512
Bone	–	0.400	0.534	0.557
Brain	–	0.419	0.494	0.544
Breasts	0.55	0.773	0.843	0.783
Eyes	–	0.751	0.855	0.876
Fetus/Uterus	0.14	0.177	0.326	0.348
Intestinal Tract	0.14	0.229	0.334	0.412
Kidney	0.24	–	–	–
Liver	0.18	0.337	0.464	0.470
Lungs	0.22	0.364	0.418	0.498
Ovaries	0.12	0.216	0.276	0.332
Pancreas	0.12	0.213	0.298	0.376
Stomach	0.18	0.369	0.475	0.490
Testes	–	0.508	0.563	0.593
Thyroid	0.45	0.569	0.525	0.533

[a]Soft tissue Kerma.

[b]Table V-6, page 162, The Effects on Populations of Exposure to Low Levels of Ionizing Radiation: 1980, National Academy Press, Washington, D.C., 1980. Isotropically incident radiation on adult phantom.

[c]Transmission calculated using reduced (6000 history) DS86 organ data base at 1500 meters from hypocenter, standing phantom, facing hypocenter.

How large are errors with current system?

- Errors in transmission factors for current 15 organs?
- Errors in using one of current 15 organs as a surrogate for some other organ?
- Initial plan: do a set of evaluative calculations using available Asian phantoms
- Working group developed a staged plan for the work

Dosimetric Uncertainty

Classical + Berkson Error

Classical + Berkson Error Model

- $W = L + U_C; \quad X = L + U_B$
  - L is some latent variable, e.g., true dose for some group
  - W is observed dose for an individual
  - X is true dose for an individual
  - U_C is classical error
  - U_B is Berkson error
- Berkson error could result from either
  - Imprecision in the input data, or
  - Some averaging or some assignment of representative values to survivors in groups
    - that is done by DS02

Adjustment of Dose Estimates for Dose Uncertainty

- Currently using method of Pierce, Stram and Vaeth with 35% classical error (1997 paper)
- Considering method of Pierce, Vaeth and Cologne with 40% classical error and additional Berkson (averaging) error (2007 paper)
- Size of Berkson error?
  - Current work