FALLOUT FORECASTS IN SURFACE AND UNDER WATER BURSTS

N. B. Cook

'The increased efficiency with which superweapons disperse radioactive materials is to some extent counter-acted by the delay in arrival of fallout from the high source cloud and the rapid rate of decay which occurs in the interim.' – R.L. Stetson, E.A. Schuert, W.W. Perkins, T.H. Shirasawa, and H.K. Chan, *Distribution and Intensity of Fallout, Operation Castle, Project 2.5a,* U.S. Naval Radiological Defense Laboratory, weapon test report WT-915, January 1956, classified 'Secret – Restricted Data' (only 240 copies printed), p. 101.

At *Operation Redwing* in 1956, rockets with radiation meters and radio-telemetry transmitters were fired through the mushroom clouds to accurately ascertain the distribution of radioactivity (see the nuclear "Weapon Test report" WT-1315). It was found that the massive visible white mushroom cloud is not radioactive fallout dust, but mostly droplets of condensed water vapour. The radioactive part is a smaller toroidal shape within the mushroom. The radius of the radioactive part varies in proportion to $W^{1/3}$ where W is the explosion yield. The visible radius depends on the air density, so is greater in tests over the Pacific Ocean than in the dry desert air of Nevada and Maralinga, so the data from desert tests (where the cloud is mainly dust) is not directly comparable to Pacific data. In reality, the visible and radioactive cloud radius and thickness both depend on $W^{1/3}$, but the *visible* cloud size also depends on the humidity (which is greater over warm oceans than dry deserts).

'During its rapid initial ascent the ball contracted horizontally … the "doughnut" or smoke ring was then formed … At first the stem was relatively narrow … At maximum it presented a very smooth appearance like a pile of inverted saucers of different diameters, stacked one upon the other … a surround formed about the narrow turbulent initial stem by condensation in outside air taking part in the vortex-ring circulation … "saucers" are the result of variations in moisture content in the atmospheric layers ...' – Dr Clarence E. Palmer, Professor of Geophysics, California University, *U.S.S. Estes* (stationed 57.5 km south of ground zero), 1952 shot *Mike,* Project 6.4b.

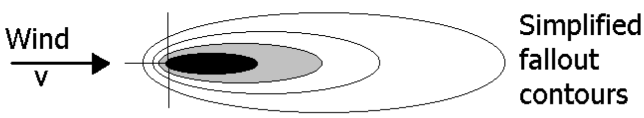
'It is obvious that the downward velocity of the particles must be affected by some mechanism other than mere gravitational settling… downdrafts occur around the central rising current and extend out to a distance of several times the diameter of the rising current.' – Charles E. Adams, *et al., Fall-out Phenomenology, Operation Greenhouse,* U.S. test report WT-4, Secret – Security Information, 1951, p. 16.

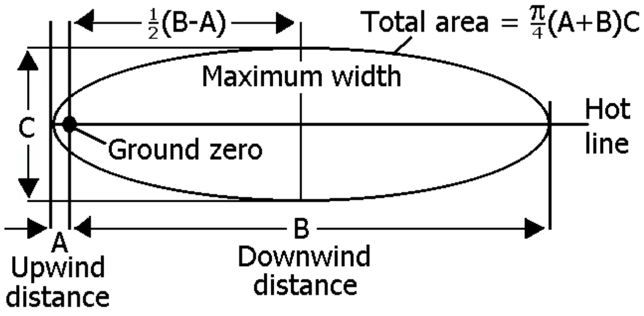
This was confirmed at the 10.4 Mt *Mike* shot in 1952:

'The cross-wind data showing the arrival time to be independent of distance can be satisfactorily explained by the vertical circulation theory as explained by Adams in the *Greenhouse* fall-out studies.' – W. B. Heidt, Jr., et al., *Nature, Intensity, and Distribution of Fall-out from Mike Shot,* report WT-615, 1953, p. 51.

The dose rates due to deposited fallout are thus increased in proportion to the cloud thickness (i.e., $W^{1/3}$), since that determines the total thickness of the fallout deposit. If the wind speed is doubled, then the same amount of fallout can spread or diffuse over *twice* as great an area before it is deposited by gravitational settling, so the thickness of the deposit is reduced by a factor of 2. Hence, fallout dose rates are inversely proportional to the wind speed, except near ground zero for the case of very low or nil average wind speed. The decrease in deposition downwind depends on the activity distribution with particle size, but related to an exponential decrease. Downwind fallout dose rate distances scale by $W^{1/3}$ for the effect of the increased cloud length, and they are also inversely proportional to wind speed, since doubling the wind speed spreads particles over twice the area. These simple physical considerations allow semi-empirical formulae for the fallout pattern.

This fallout prediction has been designed to represent DNA-EM-1 (1972) fallout graphs for any wind speed, including zero, where the fallout pattern is a series of circles surrounding ground zero, defined by the diffusive settling of the fallout cloud on to the surface below in the absence of any wind to dissipate the fallout hazard. The maximum width (C) in this case is twice the downwind distance (B), so that C = 2B. For wind speed v, the maximum width is still related to the downwind distance, but by an exponentially reduced amount as shown by the formula in the diagram.





Maximum width (as function of downwind distance):

$C = 2B \exp(-2.63v^{0.05})$, where v is in km/hour.

Downwind dose rate (along hot line):

$$R_1 = \frac{\alpha\beta f W^{1/3} \exp\{-\gamma[D(v+x)^{-1}W^{-1/3}]^{\kappa}\}}{(v+x)}$$

Upwind dose rate:

$$R_1 = \frac{\alpha\beta f W^{1/3} \exp[-\gamma(Dx^{-1}W^{-1/3})^{\kappa}]}{(v+x)}$$

SYMBOLS AND CONSTANTS

α = 65,793 R/hour at 1 hour reference time (extrapolated back from after fallout deposition is complete) for the standard height of 0.914 metre (3 feet) above a smooth, infinite, solid ground surface.

β = dose rate reduction factor for fraction of radioactivity in fallout (1 for multi-kiloton bursts, but less in sub-kiloton surface bursts, much activity is buried under ejecta within the crater), for terrain shielding (typically 0.7), for instrument response and operator shielding (0.75), so the value of β is typically $1 \times 0.7 \times 0.75 = 0.525$ to produce data for comparison with nuclear test fallout measurements made with hand-held Radiac Sets, or $1 \times 0.7 = 0.7$ to produce accurate exposure rates for study of hazards.

γ = 5.07 (for Nevada soil typical particle-size distribution)

κ = 0.45 (for Nevada soil typical particle-size distribution)

f = fission fraction of total yield = 1 for fission bombs or 0.5 for typical Teller-Ulam bombs

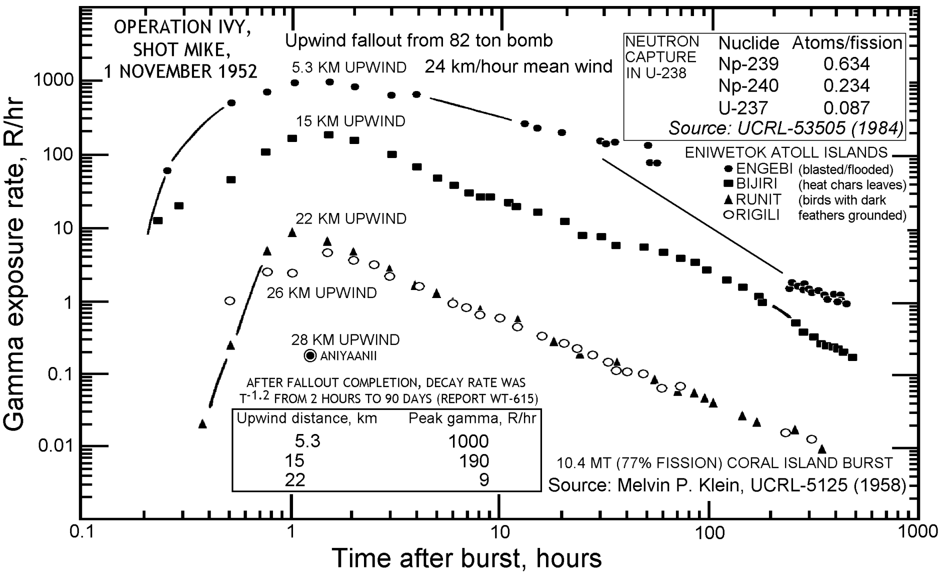
W = total yield of weapon, in kilotons

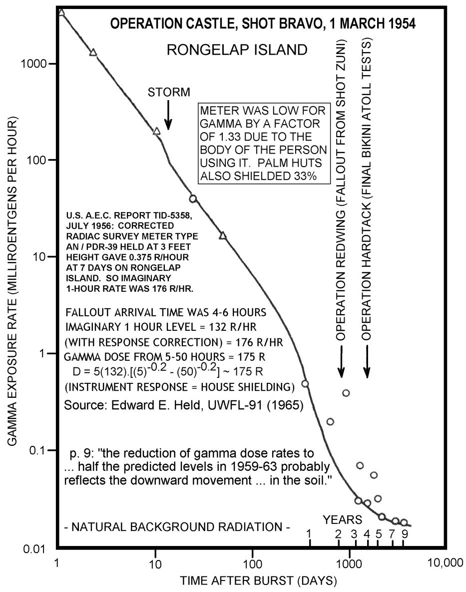
v = averaged wind speed between the surface and the top of the radioactive cloud, in km/hour

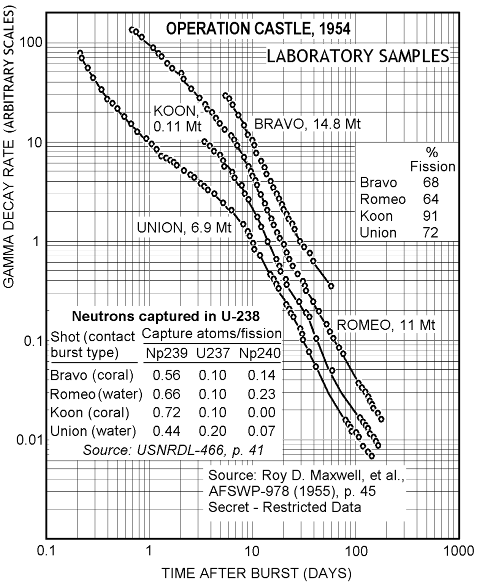
x = 0.589 km/hour = equivalent fallout diffusion speed if there is no wind.

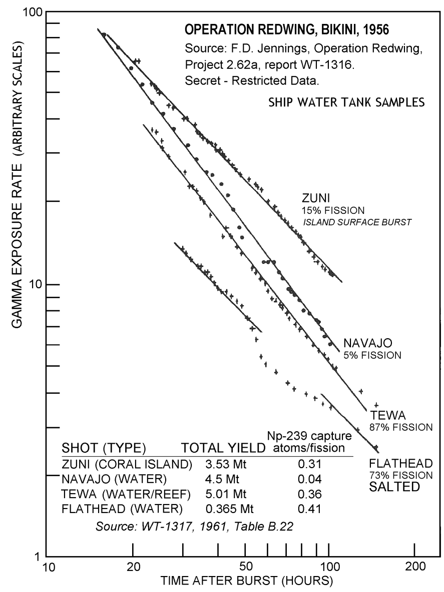
D = distance from ground zero along the 'hot line' of fallout pattern.

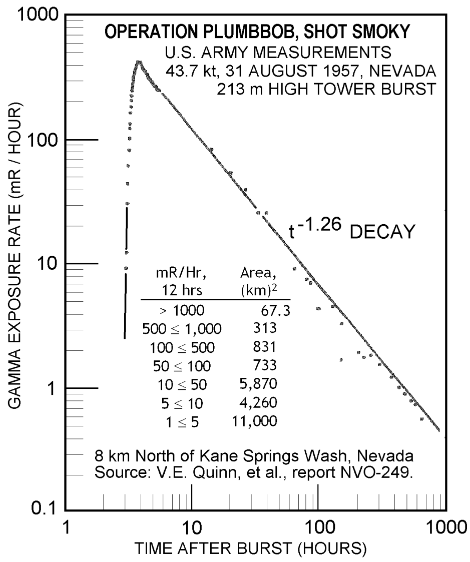
***References:* WT-1315, *Capabilities of Nuclear Weapons* DNA-EM-1 ch. 5, and nuclear test proved fallout "hot-line" (axis of maximum dose rate down wind) prediction method NRDL-TR-139, *A Fallout Forecasting Technique with Results* […].**









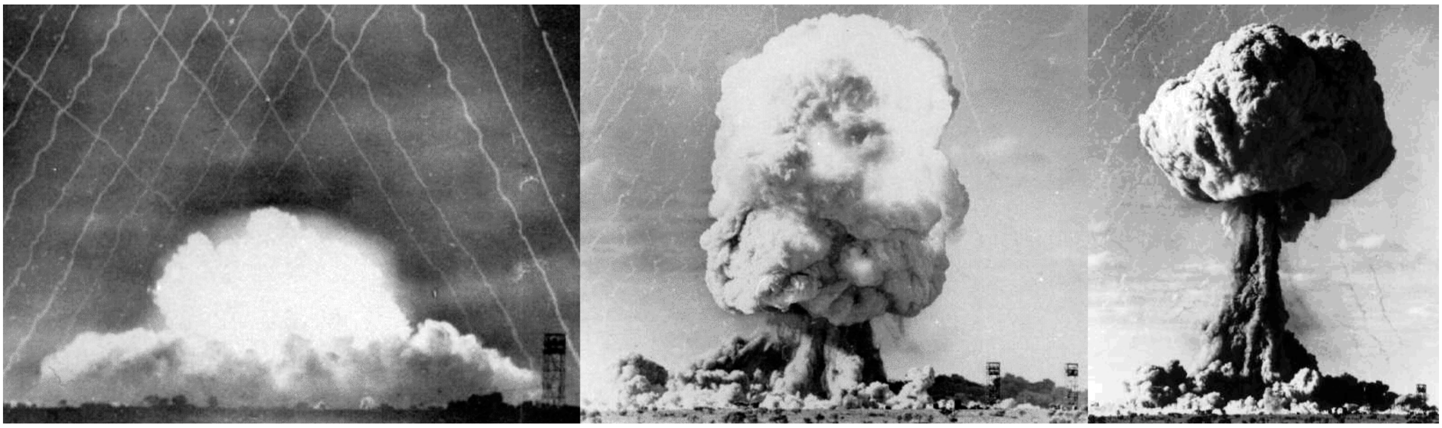


Above: Upwind fallout from test *Mike* was exceptionally intense owing to the efficient mixing of the bomb debris with large grains of coral (due to the massive, 82-ton record bomb). The *Trinity* nuclear test in 1945 proved that the average decay rate of land burst fallout between 30 minutes and 200 days after burst is roughly: $R_B = R_A (A/B)^{1.2}$, where R_A is the intensity at *A* hours after burst and R_B is the intensity at *B* hours. (Fission product fractionation and neutron-induced activities vary the exponent, but the average is always 1.2-1.3.) Integrating this gives the dose, *D,* received between times *A* and *B*: $D = 5R_A A[1 - (A/B)^{0.2}]$. If a rescue team enters a fallout-contaminated blast zone at time *T* after burst when the radiation level is *R* and they are allowed a duty dose of *D,* then their permissible duty time is: $T\{[T/(T - 0.2D/R)]^5 - 1\}$. The integrated infinite-time dose for a peak intensity *R* at time *T* after burst is *5RT* if neglecting the faster decay beyond 200 days, but taking account of this gives *4RT* (easily remembered as 'FIT Forever': *Four* times *Intensity* times *Time* gives the dose for a stay time of *Forever*). These data ignore decontamination by rain, hosing, etc.

The total gamma exposure rate from fallout, *R,* is the sum of contributions from non-fractionated (refractory) fission product decay chains, *U,* fractionated (volatile) fission product decay chains, *F,* and neutron induced activities, *I,* which are generally non-fractionated. Hence, $R = U + F + I$. The ratio of volatile to refractory activity is proportional to the ratio of surface area to volume, $1/r$, where *r* is the particle radius in microns. For *Redwing-Zuni* shot the fractionation factor was roughly $4.9/r$. The gamma dose rate due to U-238 fission is: $3015t^{-1.26}[0.43 + (2.79/r)] + I$, r/hr at 1 m above a smooth, infinite terrain, measured by an unshielded instrument, per fission kiloton deposited per square mile, for time *t* hours after detonation. Half of the beta decay rate at 1 hour is fractionated.

At 1 hour after the 18-kt *Cactus* surface burst on 6 May 1958, the gamma dose rate on the crater lip at Runit Island, Eniwetok, was 2,200 R/hr, but measurements showed it to have decayed 1,830,000-fold to 1.2 mR/hr in July 1971. Yet secrecy on fallout allowed anti-civil defence propaganda to falsely assert that salting a bomb with cobalt makes the decay rate *fast* enough to be a great danger, yet simultaneously *slow* enough to threaten life for many years! It is easy to decontaminate Co-60 fallout long before getting a lethal dose. The *greatest* hazard that can be produced is due to *fission:* neutron-induced activity from 'salted' and 'clean' bombs releases *far less radiation energy* (per neutron used) than fission, and *emits this very slowly,* with little danger to decontamination staff. Plutonium forms an insoluble dioxide in the atmosphere (or an insoluble hydroxide in underwater bursts), emits short-ranged alpha particles, and is rejected by plants.

Pu-239 has such a long half-life that it emits radiation a lower rate than alpha emitters in fallout, like Pu-238 formed when Pu-239 absorbs one neutron then emits 2 neutrons, and Pu-240, -241, and Am-241 due to neutron captures by U-238. Am-241 is the alpha source used in smoke detectors.



Above: photographs taken at 1, 8, and 20 seconds after 15-kt Australian-British nuclear test *Buffalo-1,* fired atop a 30.5 m high aluminium tower, Maralinga, Australia, 27 September 1956. Particles of silicate desert sand 'pop-corned' by the heat are being sucked into the base of the rising fireball, melted while the temperature remains high enough, and contaminated. Fallout cascades out of the top and down around the outer vortex. The background grid of smoke trails at 1 second was laid behind the fireball by rockets about 8 seconds before burst, to make the shock front position visible (the high density of the shock front between smoke trail and camera refracts light and indicates the position of the shock front by the illusion of making the smoke trail appear to 'break' at that point). *Photos:* Atomic Weapons Establishment.

Time of peak dose rate from fallout, T + ($AW^{1/3} T^{2/3}$), and time of 95% completed fallout deposition, T + ($BW^{1/3} T^{2/3}$).

All times measured in hours after burst, for fallout arrival time T, and yield W in kilotons

28 sets of data: U.K. Atomic Weapons Establishment reports AWRE-T50/57, 1957, AWRE-T43/58, 1958, and U.S. weapons test report WT-1317, 1961

Nuclear test	**Total yield, kt**	***Graphs***	**A**	**B**
Antler-1 (U.K. tower burst)	0.93	1	0.076	Not available
Buffalo-2 (U.K. ground surface burst)	1.5	3	0.114	Not available
Antler-2 (U.K. tower burst)	6.0	3	0.105	Not available
Redwing-Flathead (U.S. water surface burst)	365	5	0.238	0.419
Redwing-Zuni (coral ground surface burst)	3,530	5	0.108	0.205
Redwing-Navajo (water surface burst)	4,500	5	0.0925	0.283
Redwing-Tewa (coral harbour-type burst)	5,010	6	0.134	0.337
	Mean ± standard deviation:		**0.124 ± 0.050**	**0.311 ± 0.078**

Above: the times for fallout to build up to a peak dose rate and to be completely deposited, depend on diffusion, wind-shear and bomb yield. The further downwind (i.e. the greater the arrival time of the first fallout particles), the greater the diffusion of the cloud horizontally and vertically. The bigger the bomb yield, the bigger the cloud, so the longer it takes to pass by a given location, which naturally increases the time for the fallout deposition.

According to the testimony of Dr W. W. Kellogg to the May-June 1957 U.S. Congressional Hearings on the "Nature of Radioactive Fallout and Its Effects on Man," averaging 20 locations at 13-24 km *upwind* from 10.4 Mt *Mike* and 14.8 Mt *Bravo* surface bursts (reports WT-615, -915, and –916), the mean fallout onset time was 28 minutes. The declassified *Bravo* data report WT-915 does confirm this mean close-in (under the mushroom cloud) arrival time of 28 minutes and indicates that the peak dose rate near ground zero occurred at 1 hour after burst, with fallout particle arrival cessation occurring at a mean time of 2 hours after burst near ground zero. (See also Philip D. LaRiviere's graphs of data in his report, USNRDL-TR-139, "The relationship between the time of peak dose rate and the time of arrival of fallout.)

In the 13.5 Mt *Yankee* water surface burst at Bikini Atoll in 1954, the Nevada land-equivalent gamma dose rate corresponding to *D* metres thickness of contaminated water was 8.2*D* times that measured in the water, so water shielding gave a protection factor of 8.2*D* (WT-935, 1959). *Yankee* fallout mixed downward at 2.35 m/hour until it reached the lagoon bottom or ocean thermocline (the boundary between the warm top mixed layer of ocean and cold deep water, which occurred at a depth of 100 m near Bikini Atoll for *Yankee,* 5 May 1954, but it was only 53.5 m during Operation Redwing in July 1956). Ship and barge deck radiation at *Operation Redwing* in 1956 was a factor of 4 lower than that from similar fallout deposited on flat, open land terrain (WT-1317).

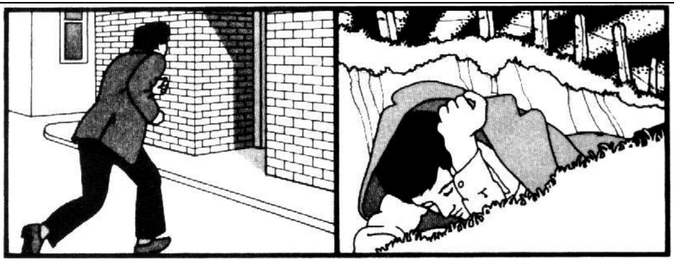
MEASURERED PROTECTION AFFORDED AGAINST 1.25 MeV MEAN ENERGY GAMMA RAYS FROM DRY DEPOSITED COBALT-60 FALLOUT (MORE PENETRATING THAN WEAPONS FALLOUT)*

SHIELDING	DOSE REDUCTION FACTOR	SHIELDING	DOSE REDUCTION FACTOR
M1 (Abrams) and M60 Tanks; M728 Engineer Vehicle	25	Bulldozer and Scraper for repairing roads, etc.	2.0
M48 Tank	50	Wood Frame House (North American design)	1.7-3.3
M2 IFV (Bradley), M3 CFV, M93 (Fox), M109, and M551	5	Hurricane Shelter/Basement under Wood Frame House	10-20
M113 Armoured Personnel Carrier, and M577 Command	3.3	Apartment Type Multi-storey Building	10-100
M548 Cargo Vehicle	1.4	Aboveground Concrete Blockhouse (23 cm thick walls)	11-140
M88 Recovery Vehicle	11	Aboveground Concrete Blockhouse (30 cm thick walls)	33-1,000
OH-58 Helicopter (parked)	1.3	Aboveground Concrete Blockhouse (61 cm thick walls)	500-10,000
UH-60 Helicopter (parked)	1.4	Partly Aboveground Shelter (61 cm thick earth cover)	50-200
CH-47 Helicopter (parked)	1.7	Partly Aboveground Shelter (91 cm thick earth cover)	200-1,000
M998 HUMMV truck, 0.75-ton truck and 2.5-ton truck	1.7	Urban Areas (in the open)	1.4
0.25-ton truck and Grader for building roads, etc.	1.3	Woods	1.3
4-ton and 7-ton trucks	2.0	Underground Shelter (91 cm thick earth cover)	5,000
M9 ACE Engineer Equipment	3.3	Open foxhole dug in the ground by a soldier	10

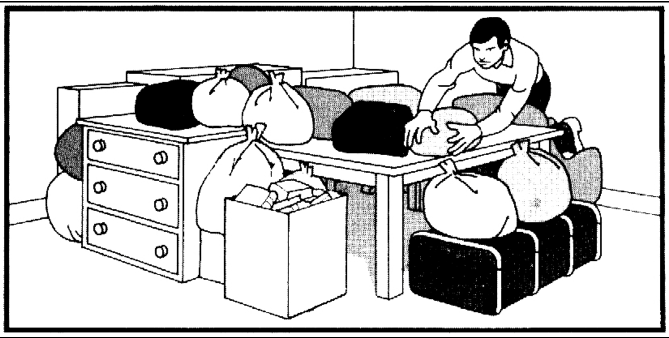
*Source: U.S. Army Field Manual 3-3-1, *Nuclear Contamination Avoidance,* Headquarters, Department of the Army, Washington, D.C., 1994 (protection is best far from roof and ground).

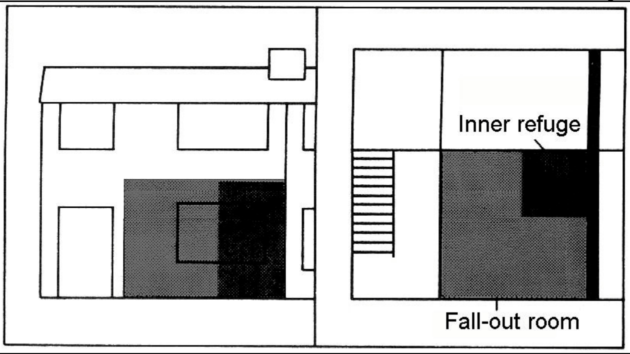
John Newman examined effects of fallout blown into a buildings, due to blast-broken windows, in *Health Physics,* vol. 13 (1967), p. 991: 'In a particular example of a seven-storey building, the internal contamination on each floor is estimated to be 2.5% of that on the roof. This contamination, if spread uniformly over the floor, reduces the protection factor on the fifth floor from 28 to 18 and in the unexposed, uncontaminated basement from 420 to 200.' But measured volcanic ash ingress, measured as the ratio of mass per unit area indoors to that on the roof, was under 0.6% even with the windows open and an 11-22 km/hour wind speed (U.S. Naval Radiological Defense Laboratory report USNRDL-TR-953, 1965). The fallout gamma exposure is from a large area, not from trivial fallout under your feet or nearby, due to the fact that on smooth terrain 50% of the dose at 1 metre height is from fallout beyond a radius of 15 metres.

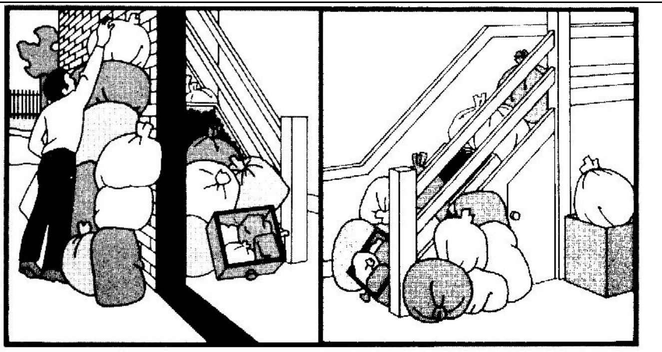
A Home Office survey of Westminster in London showed that buildings reduce the gamma dose in city streets to 52-69% of that in unobstructed terrain for dry fallout, and to 66-80% for salt-slurry fallout from seawater bursts that sticks to the windward walls (National Archives HO 226/66). The lower percentages are along streets; the higher are for crossroads. Research was done in Britain using Co-60 sources in 1955 with a 2-storey 23-cm thick brick house (U.K. report AERE.HP/R.1782). The dry fallout protection factors ranged from 8 near windows to 35 in a ground floor room with one outside wall. Weapon test fallout carried indoors gave only 3-4% of the shielded dose due to outdoor fallout (U.K. Medical Research Council, *Second Report on Nuclear and Allied Radiations …,* 1960). The small area inside a house contributed insignificant gamma radiation, compared to the much larger outdoor area surrounding being shielded by the walls. Roof fallout for 130 m^2 floor area by dry fallout, ignoring wind and rain, contributed 8.8% of the ground floor dose rate in a 2-storey wood-frame house and 31% for a similar house with 23-cm thick brick walls. In 1964, Britain conducted experiments with Co-60 sources to validate the 'core' shelter plan, published in A. D. Perryman, *Experimental Determination of Protective Factors in a Semi-Detached House With or Without Core Shelters,* U.K. Home Office CD/SA117. Using Co-60, Perryman found that the dry fallout protective factor was 21 on the ground floor of a brick house, increasing to 39 in a core shelter, made using furniture piled near an inner wall.



'... use any kind of cover, or lie flat (in a ditch) and cover the exposed skin of the head and hands. Light and heat from an explosion will last for up to twenty seconds... If after ten minutes there has been no blast wave, take cover in the nearest building.'







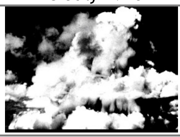
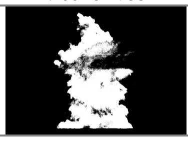
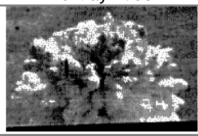
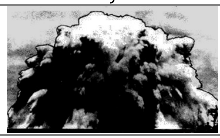
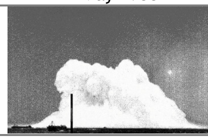
Above: 'Protect and Survive', May 1980, the British Government's 30-page manual published after Russia invaded Afghanistan in a surprise attack on Christmas Day 1979 (while Western leaders were celebrating with families). It evolved from advice on sheltering during high explosive air raids. The media did not believe that fallout decays, or that walls, furniture and bags of dirt shield dangerous radiation as they do bomb blast and fragments. The published advice seemed to 'play down' the popular horror of nuclear war: 'Choose the place furthest from the outside walls and from the roof, or which has the smallest amount of outside wall... block up the windows... Use tables if they are large enough to provide you all with shelter. Surround them and cover them with heavy furniture... Use the cupboard under the stairs if it is in your fall-out room.' This gives a good protection factor of 39 for the vital first 48 hours, when the fallout hazard is greatest: 'If you need to go to the lavatory, or to replenish food or water supplies, do not stay outside your refuge for a second longer than is necessary.'

People in the West spend on average 92% of their lives indoors, so sheltering from fallout indoors for 48 hours (when the fallout intensity has decayed 100 times from the 1-hour level) is not a massive hardship. People can shelter in buildings, basements, subway tunnels, underground rail stations, in caves, under bridges, and in underground car parks. Soldiers can shelter in ground 'foxholes', gun emplacements, trenches, tanks and armoured vehicles. An open foxhole shelter, 1.2 m in diameter and 1.2 m deep, gives a protection factor of 10 from 1.25 MeV 'hard' Co-60 gamma fallout. Some 66% of the dose received by a soldier lying in the foxhole is direct penetration through the lip (99% of this is from fallout within just 60 cm), and 34% is air-scattered, coming downwards (U.S. report NDL-TR-3, 1960). Covering this foxhole with earth-covered boards or parking a car over it (with excavated earth piled at the sides) gives a lot of extra protection. The car-over-hole shelter is in the 1974 Oak Ridge National Laboratory *Expedient Shelter Handbook* by G. A. Christy and C. H. Kearny (ORNL-4941).

UNDERWATER BURST BASE SURGE AND RAINOUT PREDICTION SYSTEM

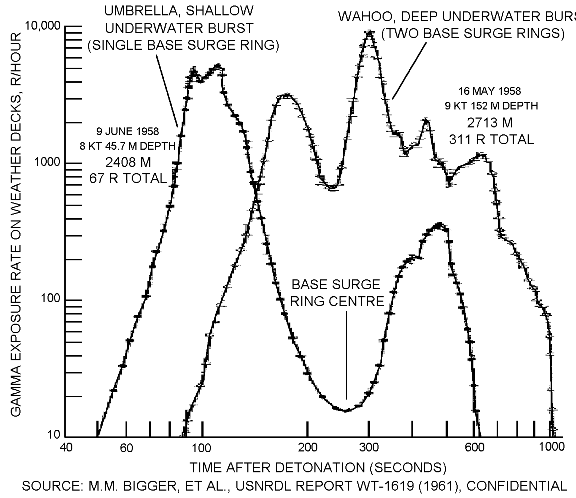
Baker, 23.5 kt at 90 ft depth in 180 ft of water, Bikini Lagoon, 25 July 1946.

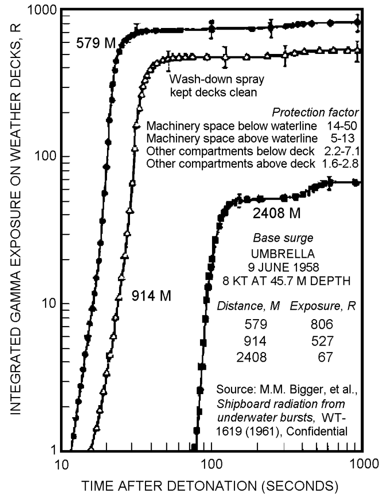
PREDICTION OF RADIOLOGICAL HAZARDS BY USING NUCLEAR TEST DATA*

BURST DEPTH ZONE	VERY-SHALLOW	SHALLOW	DEEP		VERY-DEEP
Description of phenomena	Bubble erupts through surface while it is *above* atmospheric pressure ('blow-out' of steam forms a mushroom cloud)	Bubble erupts through surface when *below* atmospheric pressure, after momentum-caused over-expansion, 'blow-in'	Bubble erupts through surface after 1-3 oscillations (expansion and contraction cycles), giving the maximum possible radioactivity to the eruption plumes that collapse to create a dangerously radioactive wind-carried base surge		Bubble completes 3 oscillations, then breaks up while underwater, so most of the radioactivity remains trapped in very deep layers
Depth of burst, d, for bursts in very deep water (m)	$6.4W^{1/3} < d < 23W^{1/3}$	$23W^{1/3} < d < 73W^{1/4}$	$73W^{1/4} < d < 210W^{1/4}$		$210W^{1/4} < d < 470W^{1/4}$
Depth of burst, d, for depth charges burst on the bottom (m)	$5.3W^{1/3} < d < 19W^{1/3}$	$19W^{1/3} < d < 63W^{1/4}$	$63W^{1/4} < d < 182W^{1/4}$		$182W^{1/4} < d < 407W^{1/4}$
Is there a 'mushroom' cloud?	Yes	No			
Shape of base surge, derived from films and measured pulses in the exposure rate measured from base surge	1 hollow disc, giving a total of 2 peaks in the base surge exposure rate (at any fixed distance downwind) as the whole of the hollow disc is blown downwind and passes overhead at any given location		2 hollow discs (one within the other) due to 2 consecutive plumes collapsing, giving a total of 4 peaks in the base surge exposure rate (at any fixed distance) as the two hollow discs drift downwind		Continuous, albeit irregular, disc, due to merged base surges from 3 consecutive rising and collapsing plumes
Example used in this table for nuclear test data, date	*Crossroads-Baker,* 25 July 1946	*Hardtack-Umbrella,* 9 June 1958	*Hardtack-Wahoo,* 16 May 1958	*Dominic-Swordfish,* 11 May 1962	*Operation Wigwam,* 14 May 1955
Photograph of plume/cloud at its maximum altitude					
Time of maximum height of plume or cloud (seconds)	60	25	15.5	16	20
Maximum height of plume or cloud (m)	2,316	1,524	536	640	442
Location	Bikini Lagoon, Pacific Ocean	Eniwetok Lagoon, Pacific Ocean	Outside Eniwetok Atoll, Pacific Ocean	740 km west of San Diego, Pacific Ocean	740 km south west of San Diego, Pacific Ocean
Measured test shot yield (kt)	23.5 (*Mk-3 bomb*)	8 (*Mk-7 bomb*)	9 (*Mk-7 bomb*)	18 (*W-44 warhead*)	32
Total depth of water (m)	54.9	45.7	975	5,220	4,880
Burst depth (m)	27.4 (*mid-depth*)	45.7 (*sea bed, in lagoon*)	152	206	610
Underwater sea bed crater	370 m *radius*, 7.6 m *depth*	460 m *radius*, 6.1 m *depth*	None		
Ratio of energy of base surge after reduction due to loss of bubble energy in ground shock and crater, to that for a burst well off the sea bed	0.56 (both *Baker* and *Umbrella* water bubbles when at maximum radius were reduced to hemispheres due to the sea bed, and lost considerable energy)		1 (*Wahoo, Swordfish* and *Wigwam* bubbles all expanded spherically; they were all sufficiently far from the sea bed to avoid any significant energy loss due to cratering or ground shock)		
Base surge top height (m) from 0.5-3 minutes	$300t^{0.55}$	$173t^{0.56}$	$213t^{0.61}$	$268t^{0.60}$	$244t^{0.69}$
Base surge radius, corrected to zero wind (m)	$1,352t^{0.51}$	$1,114t^{0.49}$	$1,484t^{0.42}$	$1,634t^{0.43}$	$1,166t^{0.31}$
Base surge radius, converted to both zero wind and to a very deep water situation (m)	$1,636t^{0.51}$	$1,354t^{0.49}$			
Accurate measurements of the peak transient gamma exposure rate on decks of ships due to base surge (dose rate falls due to both radioactive decay and a fall in airborne concentration due to cloud expansion)	4,000 R/hr at 2 min on LCT-874 (2.21 km); 220 R/hr at 6 min on APA-70 (2.96 km)	550,000 R/hr at 0.358 min on DD-474 (0.579 km); 200,000 R/hr at 0.500 min on DD-592 (0.914 km); 5,200 R/hr at 1.78 min on DD-593 (2.41 km)	17,000 R/hr at 0.80 minutes on forward and aft of EC-2 (0.701 km); 9,000 R/hr at 4.75 min on DD-593 (2.71 km)	The base surge radius was 1.83 km at 1.5 min, when the foam patch radius was 610 m. The maximum dose rate in the foam patch was 17,000 R/hr at 17 min and 100 R/hr at 3 hours	400 R/hr at 16-19 min on USS George Eastman/YAG-39 (8.53 km downwind); base surge exposure there was 30 R. Floating phosphate glass dosimeters at surface zero had 3,645 R
Radioactivity in base surge cloud (%)	1.69	1.94	95.6		17.9
Gamma exposure rate within base surge cloud (R/hr)	$29,400t^{-2.77}$	$29,400t^{-2.74}$	$559,000t^{-2.65}$	$733,000t^{-2.66}$	$527,000t^{-2.51}$
Measured residual gamma radiation on unprotected ship decks at 60 minutes (1 hour) after burst, due to condensation of base surge water and rainout	$7,085\exp(-0.618d^2)$ R/hr, where d is mean circular radius (km), due to cloud rainout that peaked at 2 minutes (4.8 km/h wind, 28.9 °C, 73% humidity)	$1.91e^{-1.18d}$ R/hr, where d is downwind distance (km), due to contamination by base surge (37 km/h wind, 30.0 °C, 63% humidity)	$39.7e^{-1.18d}$ R/hr, where d is downwind distance (km), due to contamination by base surge (27 km/h wind, 30.8 °C, 63% humidity)	*Base surge was enriched in volatile Sr-89, Sr-90 and Ba-140 decay chains which had fractionation R-factors of 22.6, 20.2, and 9.08 (water pool was depleted in these)*	9 mR/hr on the protected (water spray 'washdown' system) weather decks of the USS George Eastman/YAG-39 (8.53 km downwind)
Miscellaneous information	During the first 60 seconds, the cloud top height was $678t^{0.30}$ m, its diameter was $1,020t^{0.23}$ m, and the stem diameter was 594 m. It collapsed to form the base surge	*Downwind* total gamma doses (to 6 hours): 140 R at 0.80 km, 100 R at 1.7 km, 60 R at 2.6 km, and 20 R at 4.3 km (20 R reached 1.2 km *upwind*)	*Downwind* total gamma doses (to 6 hours): 500 R at 2.4 km, 200 R at 4.3 km, and 50 R at 7.4 km (50 R reached 1.3 km *upwind*)	Proof testing of *ASROC* (Anti-Submarine ROCket) nuclear rocket-torpedo, safely launched from the deck of the manned USS Algerholm DD-826; it travelled 4.0 km in 40 sec, only 18 m off target	33 km/hour wind. Base surge remained visible for 23 minutes. The radioactive floating 'foam patch' was visible at 1.5-13 minutes; it had a radius of $875t^{0.23}$ m
Radioactivity in torus (%)	18	0.65	4.4		2.3
Outer radius of expanding radioactive water torus (m)	$1,622t^{0.17}$	$876t^{0.17}$	$1,090t^{0.17}$	$1,375t^{0.17}$	$1,270t^{0.17}$
Vertical thickness of surface water torus (m)	54.9 (full depth of lagoon)	45.7 (full depth of lagoon)	$7.0t^{0.15}$	$8.8t^{0.15}$	110 (thermocline)
Gamma exposure rate above surface water torus (R/hr)	$17,600t^{-1.54}$	$907t^{-1.54}$	$29,200t^{-1.69}$		$2,560t^{-1.54}$

*The test examples in this table were 100% fission. W is weapon total yield, in kilotons. Times (t) are all measured in minutes after burst. American weapon test reports used in this data compilation and analysis: LAMS-439 (1946), WT-1012 (1956), WT-1014 (1962), WT-1017 (1955), WT-1608 (1962), WT-1619 (1961), WT-1621 (1962), WT-2004 (1963), DASA-1251 (1963), USNRDL-TR-687 (1963), and USNRDL-TR-68-137 (1968). The nuclear test surface water torus data from the radioactive water pool long after detonation and from 1958 measurements with underwater geiger counters, was substantiated by scaling from 13 underwater detonations of 4.5 ton chemical explosives, each containing radioactive tracer nuclides. Walter W. Perkins' report, *Hydra IIA – Comparison of High Explosive and Nuclear Underwater Explosions,* U.S. Naval Undersea Center, April 1973, report NUC-TP-345, Volume 1, AD525767, contains fractionation data for *Swordfish* and base surge size data used in obtaining the formulae in the table. The inner radius of the expanding, drifting surface water contaminated torus is 68% of the outer radius. In the *Baker* test (28.9 °C, 73% humidity air) the base surge resulted in a rainout as cool large droplets grew. In the other tests, dry air evaporated the water drops, leaving an invisible drifting cloud of small, contaminated salt crystals.

'... no weapon has ever had such potentially widespread and serious psychological aspects, nor has any weapon ever been used in war which has offered such rich opportunity for exploiting fear of the unseen and of the unknown.' – *Operation Crossroads: Radiological Decontamination Report of Target and Non-Target Vessels,* XRD-185-87, vol. 1, p. 1 (1946).





Left: the base surge consists of an expanding ring, or pair of rings (one within the other), being blown downwind. As each part of each hollow ring passes the observer, the dose rate rises to a peak. It is possible to predict the base surge by scaling nuclear test results (*see table on the next page*): for similar *scaled* depths of burst, the base surge radius in the absence of wind (R_0) is proportional to $W^{1/3}$, where W is yield. The corresponding scaled time after burst and the base surge height are both proportional to $W^{1/6}$. If the burst occurs on the seabed, much bubble energy is lost to the underwater crater, so the observed base surge radius is only 75% of that for a burst in very deep water. Wind speed v is allowed for by defining radius, $R_v = R_0 + [vt (\cos \theta)]$, where θ is the angle between the downwind direction and the line from the burst to the location of interest. The times, t, of arrival and cessation of the base surge at any location can thereby be estimated. For very shallow and shallow underwater bursts, the inner radius of the base surge ring is 67 % of the outer radius, while for deep and very deep bursts the double ring system is like a solid disc. The dose from the base surge can then be estimated by integrating the known dose rate formulae (*on the previous page*) between the relevant arrival and cessation times. The dose rate drops rapidly due to radioactive decay and dilution of airborne concentration as the surge expands, and is independent of wind speed (the effect of wind is simply to displace the centre of it in the downwind direction).

'When a constrained column of dense liquid standing on the bottom of a tank of water is released suddenly, it sinks and flows outward radially along the bottom. This action simulates the early motion of the base surge from shallow underwater explosions. Such liquid model experiments are described, scaling laws are derived, and comparisons with *Crossroads-Baker* are made. It is estimated that between 100,000 and 130,000 tons of water in the *Baker* column contributed to the surge, that the column height was between 3,500 and 4,000 feet [1.1-1.2 km], and that the column density was between 1.4 and 1.6 times that of air.' – E. Swift, Jr., *Liquid Model Studies of the Base Surge,* U.S. Naval Ordnance Laboratory report NOL-TR-62-191 (1962).

If the detonation is as deep as the 1946 *Baker* test *(photos above),* the water absorbs the flash of initial nuclear radiation, preventing E.M.P. The bulk subsidence of the water spray droplet column in air is similar to the flow of coloured dense (salty) water when poured into fresh water. Dr William G. Penney vividly described the *Baker* test base surge in a BBC broadcast as 'a thin pancake mixture spreading as it is poured into a frying pan.' Penney's secret paper on base surge predictions pointed out that the average 10-micron diameter droplets in the base surge take 562 seconds (9.4 minutes) to evaporate in 100% humidity, 20 °C warm air. In air of over 68% humidity, water evaporating from *small* droplets condenses on to the *larger* droplets, forming raindrops, with a base surge 'rainout', as in the *Baker* test (73% humidity). In dry air, water evaporates, leaving only very small salt crystals.

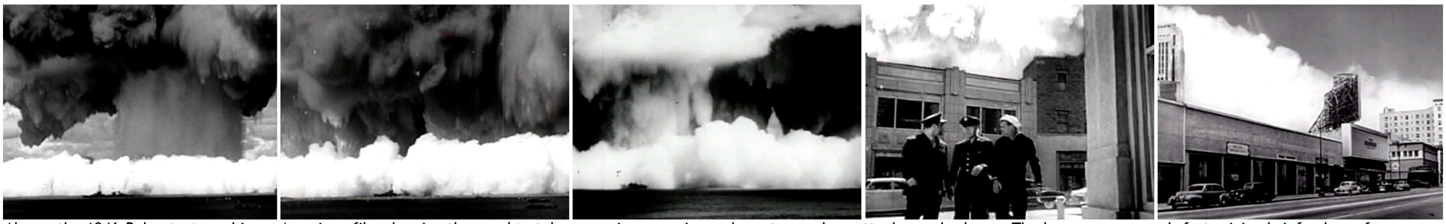
In chemical explosions underwater, the temperature falls to below 100 °C before the bubble erupts into the air, so there is no superheated salty steam column (needed to create the small droplets for a base surge). So the water droplets thrown up mechanically in chemical underwater explosions are large, and they simply fall straight back into the sea instead of flowing over the surface with air in a fluid, foggy base surge. Volcanoes can cause lethal base surges. The 1965 eruption of the Taal volcano in the Philippines caused a base surge that travelled 4 km, killing 189 people. In 1980, the eruption of Mount St Helens was instrumented, and a base surge cloud of choking hot ash mixed in air at 465 °C was filmed to roll outwards at a speed of 160 km/hour. A base surge in 79 A.D. was described as a dark cloud by the Roman eye-witness Pliny the Younger, and this killed 20,000 people in Pompeii, during the eruption of Mount Vesuvius. People cannot outrun the fast-moving close-in base surge.

At 640 m from *Baker,* a lethal human gamma dose on ship decks was recorded within just 30 seconds of detonation; at 1,550 m it was received in 7 minutes, while 2,300 m downwind it took 3 hours to accumulate (due to contamination from rainout on deck). About 88% of the maximum deposited activity from *Baker* was due to mushroom cloud rainout and 12% was deposited by the base surge. The total deck dose to 1 hour after burst due to deposited activity ranged from 140 R for the LCI-332 (1.83 km east of the detonation) to 3850 R on the *Pensacola* at 457-m south-west of the detonation). Below deck, these doses were reduced by factors of 4-40, depending on location. When sailing through contaminated waters after burst, the dose rate on deck was only 50% of the dose rate at the water surface. People can shelter below deck in ships or indoors on land, closing hatches and windows. Although the *Baker* test only sank 8 ships and seriously damaged 8 others from shock (6 of which were later deliberately sunk in Bikini Lagoon because they were irreparable), a further 42 ships were sunk *because fission products (present as charged metal ions) became chemically attached to the rusting steel.*

Decontamination was attempted by 2,000 sailors, trying to scrub and scrape decks in the humid Pacific heat without any protective clothing, but this proved of limited value against hard rust and was cancelled on 10 August 1946, due to worries about plutonium dust. The expense of sand blasting the ships clean exceeded their value to the U.S. Navy, although 22 contaminated ships were towed to San Francisco for study, and were afterwards sunk.

Region	*Average water depth*	*Region*	*Average water depth*
Pacific Ocean	4,188 m	North Sea	90 m
Atlantic Ocean	3,736 m	Baltic Sea	55 m
Indian Ocean	3,872 m	Persian Gulf	24 m
Arctic Ocean	1,205 m	English Channel	54 m

Underwater bursts effects depends on the water depth. The U.S. Naval Radiological Defense Laboratory developed and proof tested at nuclear tests the water spray "deck washdown system" to decontaminate fallout as it arrived, preventing ingress into rusty surfaces.



Above: the 1946 *Baker* test used in an American film showing the need to take cover in a surprise underwater nuclear attack on a harbour. The base surge spreads fast, giving brief pulses of radioactivity. People on land adjacent to an underwater burst, particularly if downwind, need to seek good indoor cover to shield the radiation for at least 30 minutes while the base surge disperses.

The Effects of Atomic Weapons

PREPARED FOR AND IN COOPERATION WITH THE U. S. DEPARTMENT OF DEFENSE AND THE U. S. ATOMIC ENERGY COMMISSION

Under the direction of the

LOS ALAMOS SCIENTIFIC LABORATORY

LOS ALAMOS, NEW MEXICO

Revised September 1950

BOARD OF EDITORS

J. O. HIRSCHFELDER, *Chairman* — DAVID B. PARKER

ARNOLD KRAMISH — RALPH CARLISLE SMITH

SAMUEL GLASSTONE, *Executive Editor*

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C. - Price $1.25 (paper bound)

CHAPTER I[1]

PRINCIPLES OF AN ATOMIC EXPLOSION

A. INTRODUCTION

CHARACTERISTICS OF AN ATOMIC EXPLOSION

1.1 The atomic bomb is a new weapon of great destructive power. It resembles bombs of the more conventional type in so far as its explosive effect is the result of the very rapid liberation of a large quantity of energy in a relatively small space. But it differs from other bombs in three important respects: first, the amount of energy released by an atomic bomb is a thousand or more times as great as that produced by the most powerful TNT bombs; second, the explosion of the bomb is accompanied by highly-penetrating, and deleterious, invisible rays, in addition to intense heat and light; and third, the substances which remain after the explosion are radioactive, emitting radiations capable of producing harmful consequences in living organisms. It is on account of these differences that the effects of the atomic bomb require special consideration.

1.2 A knowledge and understanding of the mechanical and radiation phenomena associated with an atomic explosion are of vital importance. The information may be utilized, on the one hand, by architects and engineers in the design of structures; while on the other hand, those responsible for civil defense, including treatment of the injured, can make preparations to deal with the emergencies that may arise from an atomic explosion.

1.3 During World War II many large cities in England, Germany, and Japan were subjected to terrific attacks by high-explosive and incendiary bombs. Yet, when proper steps had been taken for the protection of the civilian population and for the restoration of services after the bombing, there was little, if any, evidence of panic. It is the purpose of this book to state the facts concerning the atomic bomb, and to make an objective, scientific analysis of these facts. It is hoped that as a result, although it may not be feasible completely to allay fear, it will at least be possible to avoid panic.

[1] Material contributed by G. Gamow, S. Glasstone, J. O. Hirschfelder.

8.91 From measurements made at the time of the Bikini "Baker" test, it has been possible to draw some general conclusions with regard to the integrated or total radiation dosage received at various distances from surface zero.

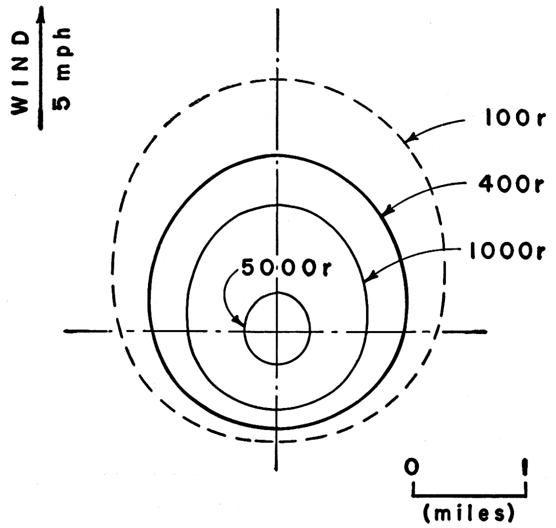


Figure 8.91a. Contours for various integrated radiation dosages due to base surge from underwater burst.

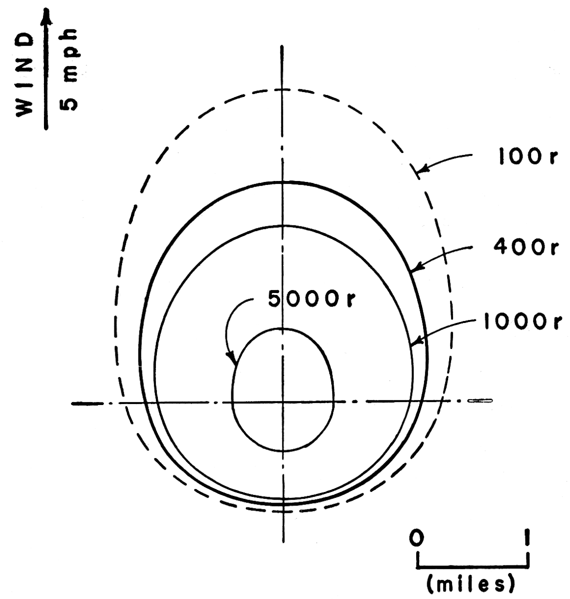


Figure 8.91b. Contours for various integrated radiation dosages due to contamination from underwater burst.

Above: During *Operation Crossroads* on 25 July 1946 an underwater nuclear explosion occurred, *Baker* (23.5 kt at 90 feet depth in 180 feet of water within Bikini Lagoon, Pacific). The mushroom cloud consisted of small sea-water droplets. After about 12 seconds the "column" or stem of the mushroom rapidly collapsed to form a radioactive wind-carried surface "base surge" mist, and rapidly spread out, enveloping and irradiating ships nearby. Then the water droplets in the mushroom cloud head fell back in a "rainout" which reached the surface about one minute after detonation, contaminating the ships. The wind affected both the base surge and the cloud rainout. In 1950, shortly after the August 1949 Russian nuclear test, the dose patterns from each phenomenon were published!

The Effects of Nuclear Weapons

SAMUEL GLASSTONE
Editor

Prepared by the
UNITED STATES DEPARTMENT OF DEFENSE
Published by the
UNITED STATES ATOMIC ENERGY COMMISSION
June 1957

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C. - Price $2.00 (paper bound)

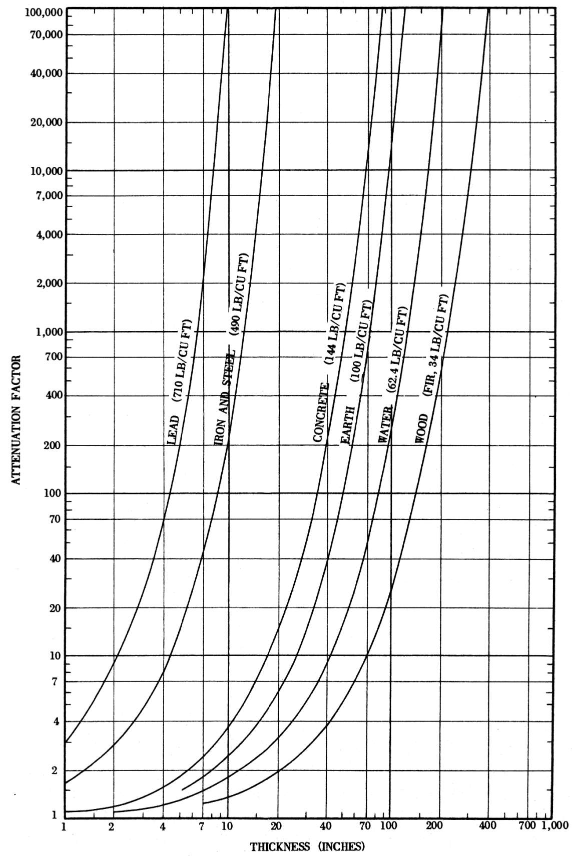
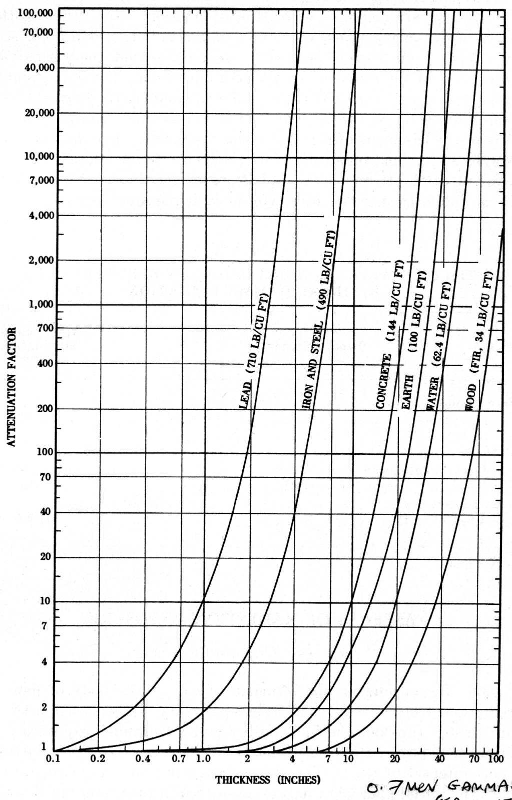


Figure 8.47. Attenuation of initial gamma radiation.



0·7MeV GAMMAS

Figure 9.36. Attenuation of fission product radiation. (FALLOUT)

12.60 In the event of a surprise attack, when there is no opportunity to take shelter, immediate action could mean the difference between life and death. The first indication of an unexpected nuclear explosion would be a sudden increase of the general illumination. It would then be imperative to avoid the instinctive tendency to look at the source of light, but rather to do everything possible to cover all exposed parts of the body. A person inside a building should immediately fall prone and crawl behind or beneath a table or desk. This will provide a partial shield against splintered glass and other flying missiles. No attempt should be made to get up until the blast wave has passed, as indicated possibly by the breaking of glass, cracking of plaster, and other signs of destruction. The sound of the explosion also signifies the arrival of the blast wave.

12.61 A person caught in the open by the sudden brightness due to a nuclear explosion, should drop to the ground while curling up to shade the bare arms, hands, neck, and face with the clothed body. Although this action may have little effect against gamma rays and neutrons, it might possibly help in reducing flash burns due to thermal radiation. The degree of protection provided will vary with the energy yield of the explosion. As stated in § 7.53, it is only with high-yield weapons that evasive action against thermal radiation is likely to be feasible. Nevertheless, there is nothing to be lost, and perhaps much to be gained, by taking such action. The curled-up position should be held until the blast wave has passed.

12.62 If shelter of some kind, no matter how minor, e. g., in a doorway, behind a tree, or in a ditch, or trench can be reached within a second, it might be possible to avoid a significant part of the initial nuclear radiation, as well as the thermal radiation. But shielding from nuclear radiation requires a considerable thickness of material and this may not be available in the open. By dropping to the ground, some advantage may be secured from the shielding provided by the terrain and surrounding objects. However, since the nuclear radiation continues to reach the earth from the atomic cloud as it rises, the protection will be only partial. Further, as a result of scattering, the radiations will come from all directions.

Above: Data on gamma radiation shielding and civil defence against fires was published in *The Effects of Nuclear Weapons.*

INTERCEPTION AND RETENTION OF FALLOUT BY PASTURE GRASS

When fallout lands on grass, most of it bounces off immediately, or falls off soon when the wind shakes the leaves and dislodges the particles. However, some fallout particles are trapped in leaf and stem bases, folds, and crevices. These are eaten with the grass by cows, and part of the fallout radioactivity which is soluble in stomach acid then contaminates the cows milk or meat.

Research during Nevada and Maralinga nuclear tests proved that a greater percentage of the smaller fallout particles are retained by crops than larger fallout particles, which are more likely to bounce off leaves and reach the ground. The exact amount retained on vegetation rather than landing on the soil is obviously dependent on how much vegetation is growing per unit area, which is denoted by Y (kg/m^2), the vegetation mass yield.

The fraction, F, of the fallout which is retained by plants is directly proportional to Y when F is very small, but when Y becomes very large, F ceases to be proportional and does not exceed 1 because that is the maximum possible proportion which can be intercepted. Hence, the formula needed is:

$$F = 1 - e^{-aY},$$

which reduces to the simple relation $F = aY$ when F is much smaller than 1, but never exceeds 1 for larger values of Y. The symbol a (m^2/kg) is the effective retention area per unit mass of vegetation.

This equation for F can be applied to any type of vegetation. For dairy pasture grass, $Y = 0.3$ kg/m^2 for average conditions in America (reference: J. J. Koranda, "Agricultural Factors Affecting the Daily Intake of Fresh Fallout by Dairy Cows", Lawrence Livermore Laboratory, California, report UCRL-12479, 1965).

The value of a depends on the sizes of the fallout particles involved. The maximum value of a is produced when the fallout consists of iodine vapour and submicron particles. This was measured precisely by Chamberlain using a variety of types of grass, yielding the result $a_{\text{vapour}} = 3.05$ m^2/kg ± 15% standard deviation (reference: A. C. Chamberlain, "Interception and Retention of Radioactive Aerosols by Vegetation", *Atmos. Environ.,* Vol. 4, 1970, p. 57).

The retention of fallout on vegetation was investigated at many nuclear tests, particularly during Operations Teapot (Nevada, 1955), Buffalo (Maralinga, 1956) and Plumbbob (Nevada, 1957). Using all these measurements with Chamberlain's value of 3.05 m^2/kg for vapours, we obtain the general equation: $a = 516/(169 + r^2)$ m^2/kg, where r is the mean radius of the fallout particles deposited at the location.

The initial danger from fallout is due to *eating fallout:* even after years of regular fallout from atmospheric nuclear tests, 80% of the Sr-90 in milk in Britain during 1958 was from cows eating fresh fallout deposited on the grass and soil, and only 20% was due to chemical uptake by roots and ingestion of older fallout in the soil (reference: J. D. Burton *et al.,* "Relationship between the Rate of Fallout and the Concentration of Strontium-90 in Human Diet in the United Kingdom", *Nature,* Vol. 185, 1960, p. 498).

It should be noted that in addition to the average of 9.1 kg/day of dry grass which is eaten by each dairy cow, it also consumes about 0.5 kg/day of soil, which gets pulled up with grass roots (reference: P. Zach and K. R. Mayoh, "Soil Ingestion by Cattle: A Neglected Pathway", *Health Physics,* Vol. 46, 1984, p. 426).

Internal Hazard from Soluble Radionuclides in Fallout

Plants can be contaminated by direct fallout deposition as well as by chemical uptake of soluble radionuclides by the fruit, leaves, stem, and roots. The direct chemical absorption of radioactivity by contaminated crops is insignificant in the first 2 weeks following any nuclear explosion, and even then is insignificant unless the fallout is relatively soluble in water, as shown by the nuclear test data (below). Decontamination can be achieved by washing fallout off crops, by discarding wheat husks and the outermost leaves of cabbages and lettuces, or by washing fruit or peeling the skin off fruit.

CHEMICAL ABSORPTION OF FALLOUT NUCLIDES BY CONTAMINATED PLANT LEAVES

Fallout nuclide solubility	Low in water	97% in water
Type of bursts	Tower bursts over silicate soil	Sea water harbour burst
Nuclear tests	Operation Teapot, 1955	Operation Hurricane, 1952
Absorption in plants of nuclides *from fallout adhering to the leaves*	Insignificant	Gradually absorption between 2 weeks and 14 months after burst
Reference	H. B. Tukey, *et al.,* "Absorption of Radionuclides by Aboveground Plant Parts and Movement within the Plant", *Agricultural and Food Chemistry,* Vol. 9, 1961, p. 107.	R. S. Russell, *et al.,* "The Effects of Operation Hurricane on Plants and Soils", U.K. Atomic Energy Research Establishment, report AERE/SPAR/3, 1955.

SILICATE FALLOUT RADIOACTIVITY SOLUBILITY DATA

British AWRE and Porton decontamination research (National Archives AWRE reports in DEFE 16 and related Porton fallout decontamination reports) showed that Australian-British nuclear test Antler over silicate soil had 1.8% and 0.4% water solubility of radioactivity for fallout particles of average radius 75 and 200 microns, respectively. At *Mosiac,* activity in particles of 1-mm radius was 0.1% water soluble, and at the *Buffalo-1* tower burst, debris of 1-cm radius had 0.01% water solubility. Silicate sand (SiO_2) has a density of 1.54 grams per cubic centimetre, and comprises 80% of soil above $CaCO_3$ rock at the Australian-British Maralinga test site. Silicate minerals are the most common in the Earth's crust, forming the most rock and sand. Pure silicate (quartz) sand particles ejected from the crater remain liquid at temperatures below 2,950 °C, and re-solidify into insoluble glass spheres when the fireball temperature falls below 1,607 °C. Before this time, condensing fission products diffuse inside molten glass droplets, creating insoluble radioactive particles, but at later times fission products are deposited on the outside of solidified glass, giving soluble (biologically available) radioactivity. I-131 on the outer surfaces of fallout particles is in the soluble –1 oxidation state (U.S. test report WT-917). Water-soluble activity is located in an outer 0.35-micron deposit on the glass, while the soluble fraction for stomach acid (0.1 N HCl, pH4) is equivalent to a deposit 10 microns thick. The insoluble fraction of the volume equals the volume of the inner insoluble glass sphere divided into the effective total volume including the soluble outer deposit: $(4/3)\pi r^3/[(4/3)\pi(r + X)^3] = (1 + X/r)^{-3}$, where X is the thickness of the soluble deposit (0.35 and 10 microns respectively for water and acid) and r is the insoluble glass radius, measured in the same units. So the soluble activity percentage for silicate fallout is simply $100[1 - (1 + X/r)^{-3}]$ %.

FALLOUT FROM BURSTS ON LIMESTONE, CORAL, AND SEA WATER

American Pacific land surface bursts which occurred over coral sand (like chalk and limestone, calcium carbonate) were $CaCO_3$, which dissociates into CO_2 and CaO when heated to a temperature of 850 °C in the fireball. CaO melts at 2,570 °C, which must be reached for the core of the particle to be uniformly contaminated with fission products. The outside of the CaO core reacts with atmospheric moisture to form a calcium hydroxide layer during fallout: $CaO + H_2O \rightarrow Ca(OH)_2$. Reaction of the outer surface of this calcium hydroxide layer, $Ca(OH)_2$ with atmospheric CO_2 at temperatures below 30 °C creates an outer shell of $CaCO_3 + H_2O$. About 38.5% by mass of particles in the 1956 *Zuni* coral surface burst test had surface contamination only, but 98.7% of the radioactivity was contained in uniformly contaminated particles. The fallout density for coral bursts ranged from 2.36 grams per cubic centimetre for *Bravo* to 2.46 for *Zuni* (Weapon test report WT-1317).

The *Redwing-Inca* steel tower test over coral soil in 1956 was a 15.2 kt-bomb was fired on top of a 61-m steel tower (containing 165 tons of iron) over coral sand at Eniwetok Atoll. Magnetite (Fe_3O_4) particles formed, and the mixed coral and steel formed marbles of contaminated black dicalcium ferrite ($2CaO.Fe_2O_3$) with veins of uncontaminated calcium hydroxide. By measuring the ratio of calcium to iron in the fallout, the mass of coral converted into fallout was found to be 264 tons. Only the top 2 mm of the sand around ground zero was thus swept up by the afterwinds:

'The fact that only a thin layer of sand was actually either vaporized or melted, even though in contact with the fireball... indicates that the thermal effects penetrate only superficially into solid material during the short duration of the very high temperatures. By computing the energy required to heat, decarbonate, and melt 264 tons of coral sand and to heat, melt and vaporize 165 tons of iron ... 8.5% of the available radiant energy [*i.e., 3% of bomb yield, because the radiant energy was 35% of the total energy of the explosion*] was utilised for heating the tower and soil material.'

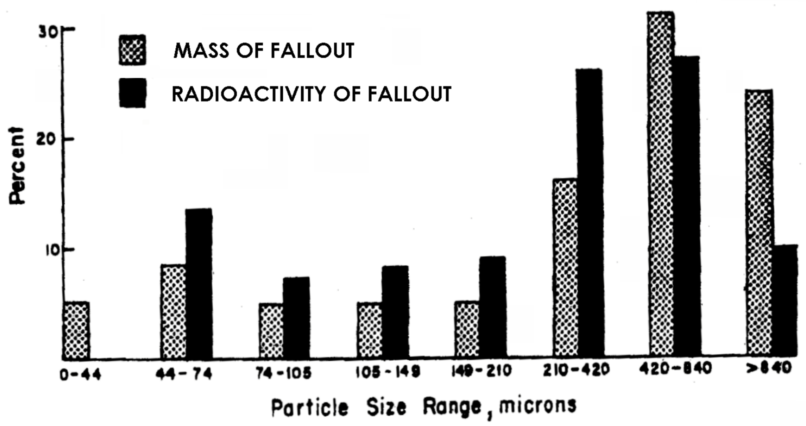
- Charles E. Adams and J.D. O'Connor, U.S. Naval Radiological Defense Laboratory, report USNRDL-TR-208, 1957, p. 13. (Comparison of the fallout particle photographs in the unclassified report USNRDL-TR-208 report with page 94 of the declassified report WT-1317 identifies the test described in USNRDL-TR-208 as being *Redwing-Inca*.)

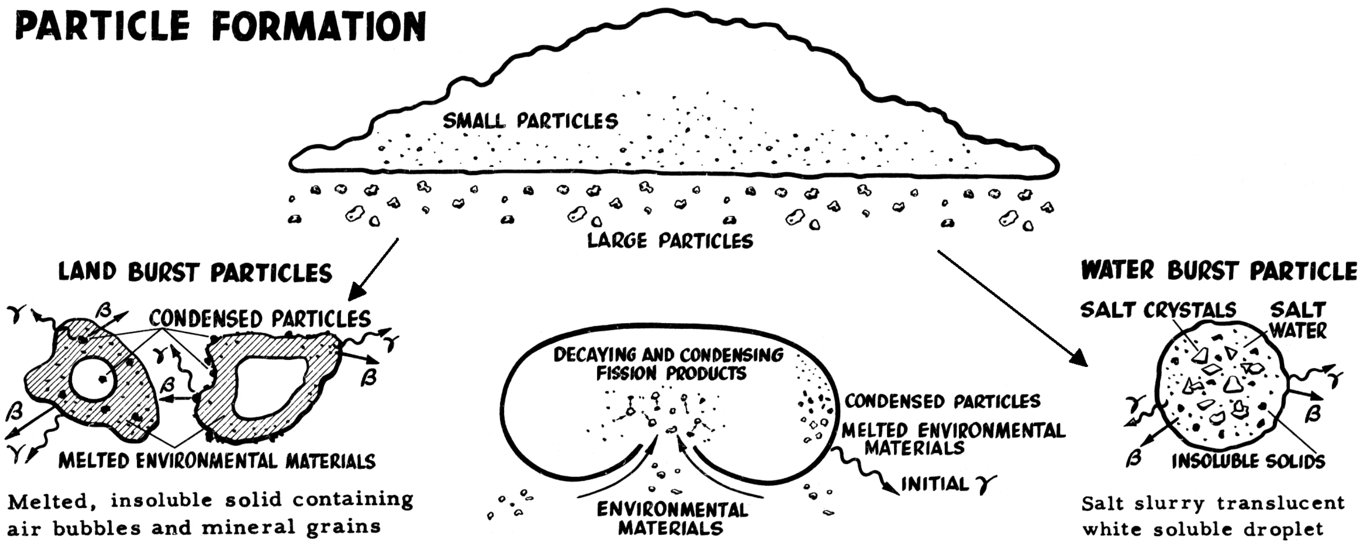
HEAVIEST RECORDED CLOSE-IN FALLOUT DEPOSITS FROM SEA WATER SURFACE BURSTS FLATHEAD AND NAVAJO, AND CORAL SURFACVE BURSTS ZUNI AND TEWA (TEWA WAS A 5 MEGATON BURST OVER RELATIVELY SHALLOW WATER, SO WAS APPROXIMATELY A CORAL BURST)

TEST (DATA: USNRDL-466 AND WT-1317)	*Distance* (barge station)	Fallout arrival, min.	Fallout peak, hr	Peak deck dose rate, R/hr	Time for 95% fallout down, hr	Fallout mass, g/m²
***Flathead*, 365 kt (73% fission)**	**10 km (YFNB 13)**	**21**	**1.3**	**21.8**	**2.0**	**66.3**
***Navajo*, 4.5 Mt (5% fission)**	**12 km (YFNB 13)**	**12**	**0.63**	**8.5**	**1.9**	**55.8**
***Zuni*, 3.53 Mt (15% fission)**	**17 km (YFNB 29)**	**19**	**0.82**	**9.6**	**2.4**	**40.6**
***Tewa*, 5.01 Mt (87% fission)**	**13 km (YFNB 29)**	**14**	**1.7**	**40**	**4.3**	**48.8**

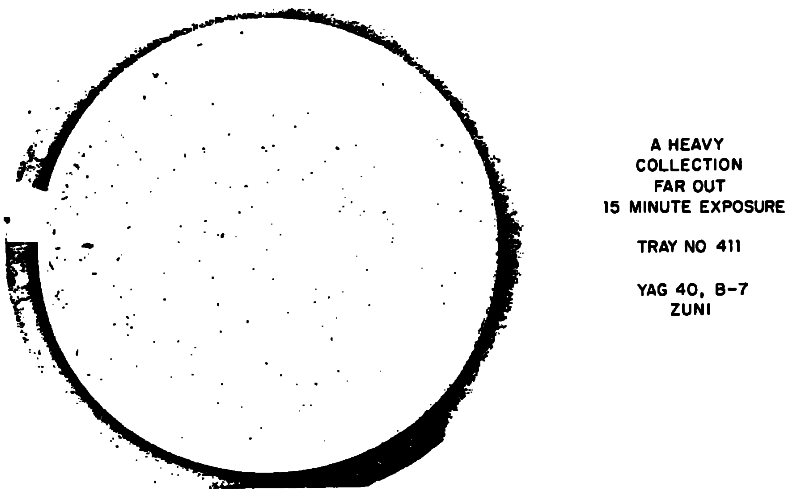
Sources: USNRDL-466 (1961) and WT-1317 (1961). All times are measured from detonation time. The peak deck dose rates are 4 times lower than land dose rates from the same fallout deposit, due to the limited area of contaminated decks and shielding by the superstructure of the barge. Some sea water was included in all the fallout: summing the measured data for all ships, barges and islands (WT-1317, page 67) indicates that the mass of coral products in the fallout was 0.30% of the total for *Flathead,* 1.2% for *Navajo,* 74% for *Zuni,* and 88% for *Tewa.*

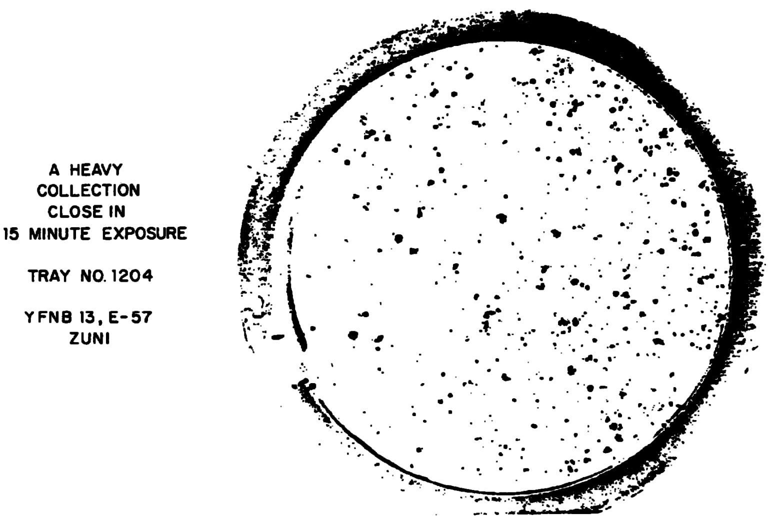
3.53 MT ZUNI FALLOUT PARTICLE SIZE DISTRIBUTION AT 23.8 KM DOWNWIND SAMPLE FROM CHARLIE (NAMU) ISLAND (Source: M. Morgenthan, Land Fallout Studies, ITR-1319, AD338529, Fig. 3.49.)



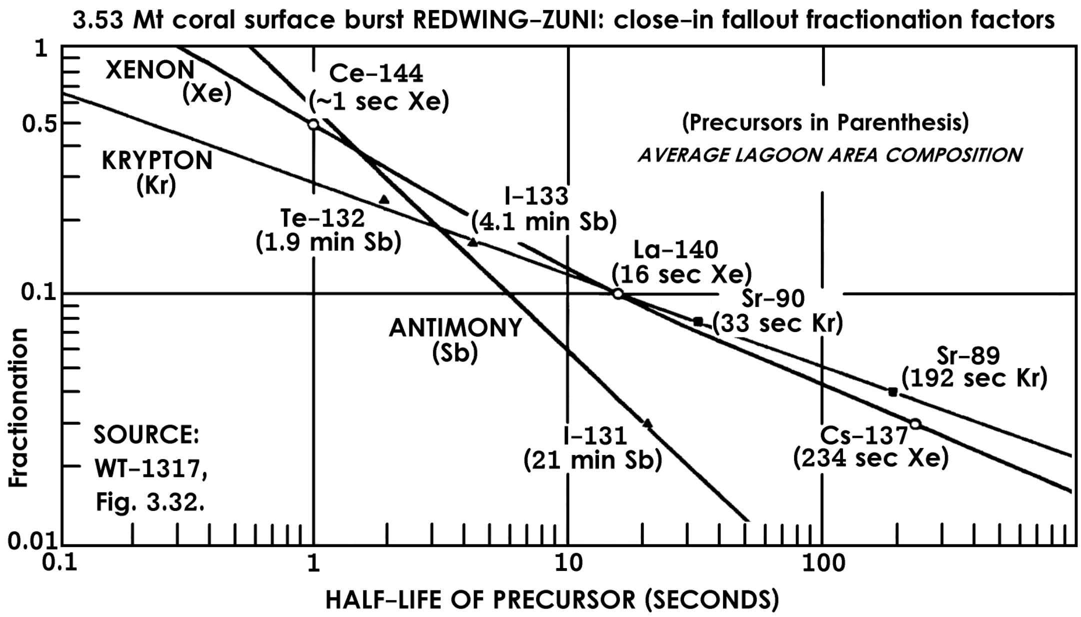


Above: lethal fallout is not an invisible gas that can only be detected by special instruments. It must be carried down from high altitudes rapidly on large, visible particles or droplets in order to produce high doses before the radioactivity decays to insignificance. Only the Marshallese who saw *visible* fallout deposited from the 1954 *Castle-Bravo* 14.8 megaton coral reef surface burst 115 miles away received beta burns to bare skin, and they were burned only on moist areas of skin and coconut oil dressed hair that retained fallout for many hours. *Because ordinary clothing did not retain the dry fallout particles, clothed areas were protected from beta radiation exposure.* This protection by clothing has *nothing to do with beta radiation shielding:* clothing offers protection *by not retaining fallout for long periods, unlike sweaty skin areas*. However, waterproof clothing is required for protection against wet sticky fallout particles from water surface bursts in humid air. This is because wet fallout can soak through porous clothing and drench skin, which can cause fatal beta burns as occurred to water drenched firemen who attempted to put out the nuclear reactor at Chernobyl in 1986. (Illustration adapted from Dr Triffet's testimony before the Special Subcommittee on Radiation, June 1959.)

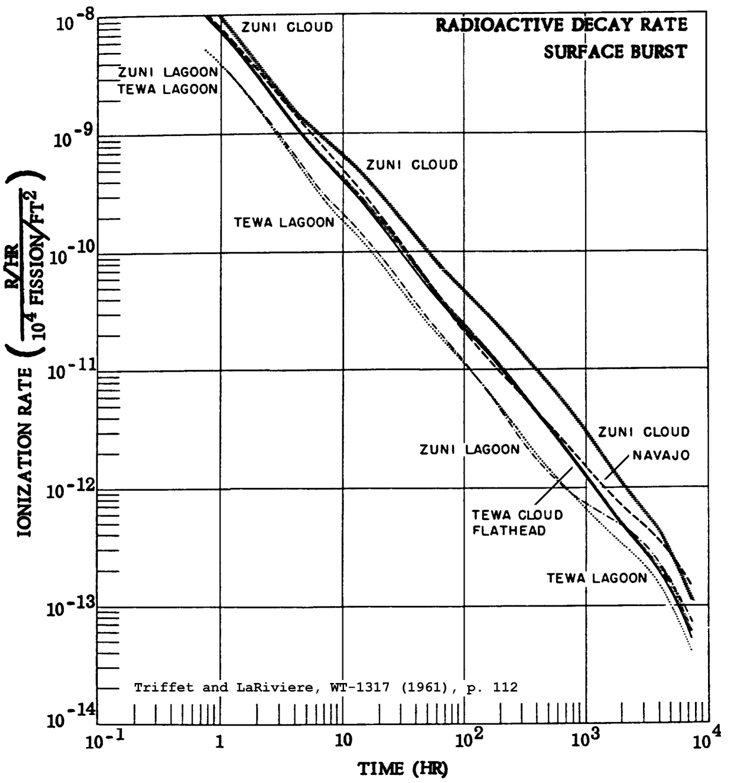




Above: surface bursts loft hundreds of tons of soil/kt as fallout, so the specific activity per unit mass of fallout is relatively low, and the carrier soil makes the fallout clearly visible where there is a lethal hazard. You do not need radiation meters to determine that a lethal fallout hazard exists. These 8.1 cm-diameter trays were exposed for just 15 minutes (report WT-1317).



Above: close-in fallout from surface bursts is *fractionated,* with greatly reduced abundances of the soluble volatile fission product like iodine-131, which can only plate the outer surfaces of fallout particles in the later stages of fireball condensation. This graph is from Terry Triffet and Philip D. LaRiviere's report *Operation Redwing, Characterization of Fallout,* WT-1317, 1961. It shows that there is a correlation between fractionation and the half-life of the volatile precursor in each "decay chain".



Above: surface burst radioactivity decay rates depend on fractionation and neutron induced activities such as Np-239 and U-237 produced by neutron capture reactions with U-238 in the bomb. But *Zuni* (3.53 Mt 15% fission coral island surface burst), *Tewa* (5.01 Mt 87% fission coral reef surface burst), *Flathead* (365 kt 73% fission ocean surface burst) and *Navajo* (clean 4.5 Mt 5% fission ocean surface burst) all lead to a fractionated (lagoon) and unfractionated (cloud) fallout decay which is roughly similar, ~$(\text{time})^{-1.2}$.

				Number of neutron capture atoms per fission in fallout samples		
Test shot	*Weapon design*	*Yield*	*Fission %*	*U-239 & Np-239*	*U-237*	*U-240 & Np-240*
Jangle-Sugar	U238 reflector	1.2 kt	100	0.59		
Jangle-Uncle	U238 reflector	1.2 kt	100	0.59		
Castle-Bravo	U238 pusher	14.8 Mt	68	0.56	0.10	0.14
Castle-Romeo	U238 pusher	11 Mt	64	0.66	0.10	0.23
Castle-Koon	U238 pusher	110 kt	91	0.72	0.10	
Castle-Union	U238 pusher	6.9 Mt	72	0.44	0.20	0.07
Redwing-Zuni		3.53 Mt	15	0.31**	0.20	0.005
Redwing-Tewa		5.01 Mt	87	0.36	0.20	0.09
Diablo	U238 in core**	18 kt	100	0.10		
Shasta	U238 in core**	16 kt	100	0.10		
Coulomb C	U238 in core**	0.6 kt	100	0.03		

* Dr Carl F. Miller, report USNRDL-466 (1961). U-237 is produced by >6.2 MeV neutrons in the (n,2n) reaction with U-238. WT-1315 page 12 gives slightly different results: 0.427 atoms of U-239 from neutron capture per fission for *Zuni,* 0.500 for *Cherokee,* and 0.125 for *Navajo.* ** In these *Plumbbob* weapon tests, there was no U238 reflector and the only U238 in the bomb was that contained in the fissile core as an impurity.

Measured relationship between the fusion yield of the nuclear explosive and the quantity of neutron-induced activities in the fallout*

Test shot		*Redwing-Navajo*	*Redwing-Zuni*	*Redwing-Tewa*	
Fusion stage pusher		Lead (Pb)	Lead (Pb)	U-238	
Total yield		4.5 Mt	3.53 Mt	5.01 Mt	
% Fission		5	15	87	
% Fusion		95	85	13	
Nuclide	*Half life*	*Abundance of nuclide in bomb fallout, atoms per bomb fission*			R_1**
Na-24	15 hours	0.0314	0.0109	0.00284	1284.7
Cr-51	27.2 days	0.0120	0.00173	0.000297	0.280
Mn-54	304 days	0.10	0.011	0.00053	0.614
Mn-56	2.58 hours	0.094	0.011		2668
Fe-59	45.2 days	0.0033	0.00041	0.000167	6.19
Co-57	272 days	0.00224	0.0031	0.000182	0.113
Co-58	71 days	0.00193	0.0036	0.000289	3.11
Co-60	5.27 years	0.0087	0.00264	0.00081	0.299
Cu-64	12.8 hours	0.0278	0.0090	0.00228	89.5
Sb-122	2.75 days		0.219 (cloud), 0.0252 (lagoon)		38.4
Sb-124	60 days		0.073 (cloud), 0.0084 (lagoon)		6.92
Ta-180	8.15 hours	0.038	0.0411 (cloud), 0.0691 (lagoon)		35.9
Ta-182	114 days	0.038	0.0194 (cloud), 0.0326 (lagoon)	0.01 (cloud), 0.006 (lagoon)	2.67
Au-198	2.7 days				36.9 [*Flathead* test]
Pb-203	52 hours	0.0993	0.050	0.0000178	26.0
U-237	6.75 days		0.20	0.20	6.50
U-239	23.5 minutes	0.125***	0.31***	0.36	173
Np-239	56.4 hours	0.125***	0.31***	0.36	14.9‡
U-240	14.1 hours		0.005	0.09	0 (no gamma rays)
Np-240	7.3 minutes		0.005	0.09	150

*Dr Terry Triffet and Philip D. LaRiviere, *Characterization of Fallout, Operation Redwing, Project 2.63,* U.S. Naval Radiological Defense Laboratory, 1961, report WT-1317, Table B.22. Data on U-238 capture nuclides is from Dr Carl F. Miller, USNRDL-466, Table 6 (compare with WT-1315, Table 4.1).

**Triffet's 1961 values for the gamma dose rate at 1 hour after burst at 3 ft above an infinite, smooth, uniformly contaminated plane, using an ideal measuring instrument with no shielding from the person holding the instrument, from 1 atom/fission of induced activity, (R/hr)/(fission kt/square stat mile).

*** WT-1315 page 12 gives slightly different results: 0.427 atoms of U-239 from neutron capture per fission for *Zuni*, 0.500 for *Cherokee*, and 0.125 for *Navajo*.

†*Zuni* contained antimony (Sb), which melts at 903.7K and boils at 1650K. The abundances of Sb-122 and Sb-124 given in the table are for unfractionated cloud samples; because of the low boiling point of antimony, it was fractionated in close-in fallout, so the abundances of both Sb-122 and Sb-124 in the *Zuni* fallout at Bikini Lagoon were 8.7 times lower than the unfractionated cloud fallout data shown in this table.

‡Note that Np-239 at 1 hour after burst is still forming as the decay product of U-239.

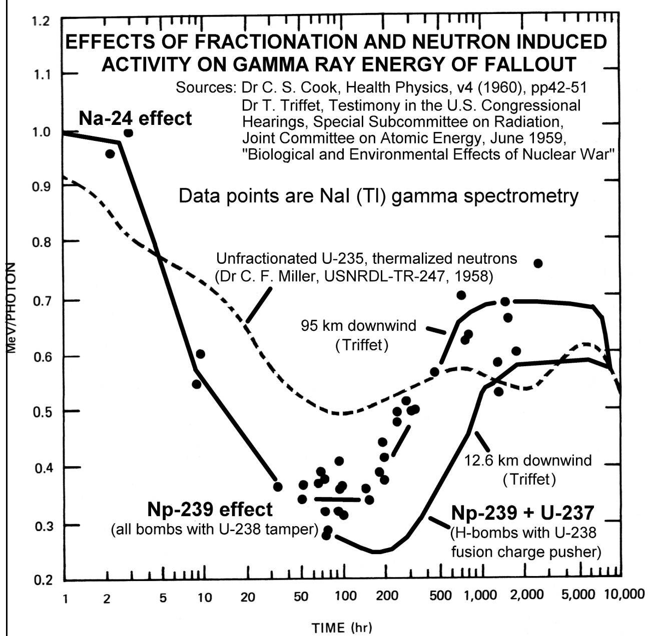
Above: The *low energy of gamma rays from Np-239 and U-237 in the first couple of weeks makes it easier to shield gamma from U-238 cased "dirty" weapons*. The original anti-civil defense propaganda on fallout in the 1950s and 1960s originated from false claims about neutron induced activity affecting the decay rate of the fallout substantially for salted or cobalt-60 weapons, e.g. Shute's novel *On the Beach* and the Kubrick film *Dr Strangelove*. But for each neutron used for the fission of U-238 you get 200 MeV of energy, *including far more residual radioactivity energy than from capturing the neutron in cobalt-59 to produce cobalt-60*. The smaller dose of gamma ray energy from the cobalt-60 *gets spread over a longer period of time, producing smaller dose rates, enabling decontamination to wash the fallout away before a high dose is accumulated.* There is also a serious fractionation difficulty for cobalt-60 in widespread fallout, which was classified secret for decades. Because cobalt is highly refractory unlike volatile fission product decay chain precursors, most of it is deposited near the crater region in very large, fast-falling particles. Whereas iodine-131 and caesium-137 are depleted from local fallout and enriched in distant fallout, the opposite is true of refractory elements like cobalt.

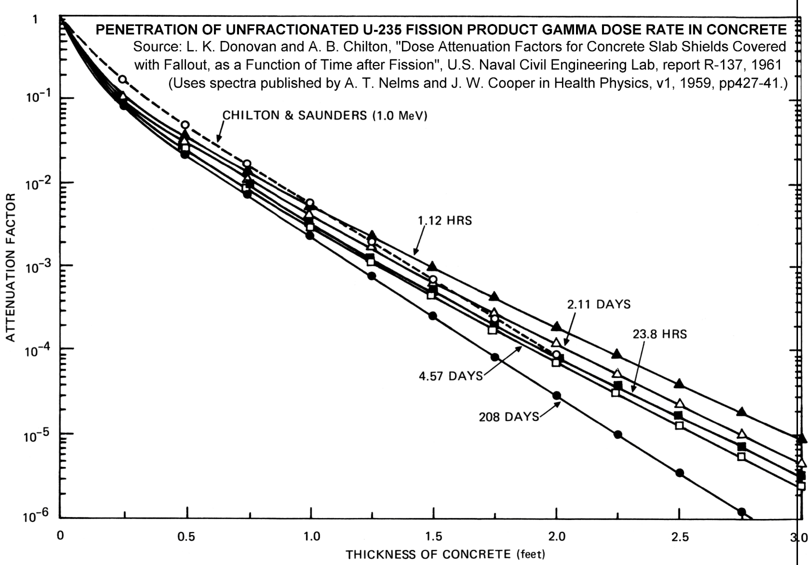
A 1957 British nuclear test in Australia was "salted" with cobalt-59 to produce Co-60 in the fallout, primarily as a diagnostic "tracer" tool. Because it is refractory, the cobalt ended up located in 180 large "metallic-looking" 1-2 mm diameter pellets containing a total of 4.5 curies of Co-60. These particles contained an average of 25 mCi of Co-60, with the largest particle of 2 mm diameter containing 79 mCi of Co-60), all located within a 100,000 square foot area about 700 feet North of *Antler-Tadje* ground zero (reported by O. H. Turner of AHPR to C. G. Dale at AWRE in 1958). This is no use for making the world uninhabitable. America "salted" the fallout from the *Redwing-Flathead* test at Bikini in 1956 with radioactive gold, Au-198 (2.7 days half-life) formed by simply adding gold to the nuclear weapon (see report WT-1317). Au-198 produces its maximum percentage contribution to the radiation from fallout at $2.7(1.2/\ln 2) = 4.7$ days after burst. A greater damaging effect is obtained by simply adding natural uranium to a bomb casing to cause more fission, rather than to try to soak up unmoderated fission spectrum neutrons using a case of salt, cobalt, or gold.

Decontamination can wash away the fallout particles carrying insoluble radioactivity, although initially water soluble fission products present as metal ions can chemically bind to surfaces once the fallout, and are then more difficult to remove. Dr Carl F. Miller demonstrates this for the case of water surface burst fallout (wet, ionic salt crystals in a slurry with water) in volume 2 of his report *Fallout and Radiological Countermeasures,* Stanford Research Institute, January 1963 (AD410521), Figure 8.3. At 100 hours after a sea water surface detonation, 67% of the gamma dose rate from wet fallout will remain on Navy grey ship paint after water washing, i.e., 67% of the gamma emission rate is from ionic fission products which have become chemically attached to the paint. This percentage falls to just 31% at 500 hours after detonation, then increases again, reaching 70% at 6,500 hours. As the ratio of total activity from the chemically insoluble and chemically soluble fission products varies with time, so does the overall solubility and decontamination effectiveness for ocean burst fallout.

Spectrum of fission product gamma rays from the thermonuclear neutron fission of U-238 (Glenn R. Crocker, *Radiation Properties of Fractionated Fallout; Predictions of Activities, Exposure Rates and Gamma Spectra for Selected Situations,* U.S. Naval Radiological Defense Laboratory, USNRDL-TR-68-134, 27 June 1968, 287 pp.)

Gamma ray energy, MeV	Fission product gamma spectrum at 1 hour				Fission product gamma spectrum at 1 week			
	Sr-89 abundance (relative to unfractionated fallout)				Sr-89 abundance (relative to unfractionated fallout)			
	10% $R_{89,95} = 0.1$	50% $R_{89,95} = 0.5$	100% $R_{89,95} = 1$*	200% $R_{89,95} = 2$	10% $R_{89,95} = 0.1$	50% $R_{89,95} = 0.5$	100% $R_{89,95} = 1$*	200% $R_{89,95} = 2$
0-0.5	0.396	0.354	0.350	0.304	0.695	0.662	0.678	0.637
0.5-1	0.385	0.379	0.363	0.357	0.262	0.270	0.245	0.265
1-1.5	0.1605	0.1863	0.1914	0.232	0.01339	0.01358	0.01218	0.01273
1.5-2	0.0327	0.0466	0.0558	0.0596	0.0287	0.0519	0.0591	0.0790
2-2.5	0.01628	0.0203	0.0279	0.0290	0.001114	0.001313	0.001268	0.001445
2.5-3	0.00429	0.00717	0.01192	0.01305	0.001372	0.00253	0.00291	0.00388
3-3.5	0.00340	0.00301	0.00267	0.00273	0.0000260	0.0000490	0.0000564	0.0000760
3.5-4	0.001425	0.001187	0.001705	0.00214	0	0	0	0
Total:	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Relative gamma activity	0.547	0.756	1	1.25	0.563	0.768	1	1.12
Mean energy, MeV	0.710	0.767	0.807	0.856	0.444	0.486	0.483	0.526





Above: fallout radiation protection factor calculations are traditionally made assuming the 1.25 MeV mean gamma ray energy of cobalt-60, not the wider spectrum of actual gamma rays from bomb fallout. This leads to substantial underestimates of protection factors which are smaller than 100. The effect of Np-239 and U-237 (which make a maximum percentage contribution to $t^{-1.2}$ fallout decay radiation at a time of 1.2/ln2 = 1.73 times their respective half-lives of 56 hours and 6.8 days, i.e. 97 hours and 12 days, respectively) further softens the gamma ray spectrum, increasing the benefits of any shielding, as explained by *Operation Redwing* fallout characterization project officer Dr Terry Triffet to congress in June 1959.

Dr Triffet at the 22-26 June 1959 Congressional Hearings on the *Biological and Environmental Effects of Nuclear War* pages 61-111 showed that at 1 week after burst, the mean gamma ray energy of fractionated fallout 8 statute miles downwind of a megaton range surface burst was 0.25 MeV, while at 60 statute miles downwind it was 0.35 MeV (due to less depletion of high energy fission products at greater distances, a fractionation effect). On page 205 of the June 1959 hearings on the *Biological and Environmental Effects of Nuclear War,* Dr Triffet explained that the low gamma ray energy makes most of the radiation very easy to shield by improvised emergency countermeasures:

"I thought this might be an appropriate place to comment on the variation of the average energy. It is clear when you think of shielding, because the effectiveness of shielding depends directly on the average energy radiation from the deposited material. As I mentioned, Dr Cook at our [U.S. Naval Radiological Defense] laboratory has done quite a bit of work on this. ... if induced products are important in the bomb [i.e. in high fission devices employing U-238 ablative "pushers" or fusion capsule jackets], there are a lot of radiations emanating from these, but the energy is low so it operates to reduce the average energy in this period and shielding is immensely more effective."

There is extensive data on the gamma ray spectrum of fallout from the *Zuni, Tewa, Flathead* and *Navajo* surface bursts in Table B.21 of Triffet and LaRiviere's 1961 report *Characterization of Fallout* (WT-1317) and in Tables 1 and 2 of W. E. Thompson's report *Spectrometric Analysis of Gamma Radiation from Fallout from Operation Redwing* (U. S. Naval Radiological Defense Laboratory technical report USNRDL-TR-146, 1957). For example, Thompson gives the detailed spectrum of gamma radiation measured on Bikini Island (codenamed How Island, fallout collector F-61, sample GA) at 13 miles east-north-east of ground zero for the 3.53 Mt 15% fission coral surface burst *Zuni*. At 10 days after this detonation, the mean gamma ray energy emitted by this sample was just 0.218 MeV. Since shielding thicknesses are roughly proportional to the square root of the gamma ray energy, shielding thicknesses needed for a given protection factor at this time were 2.4 times smaller than for cobalt-60 gamma radiation (1.25 MeV mean).

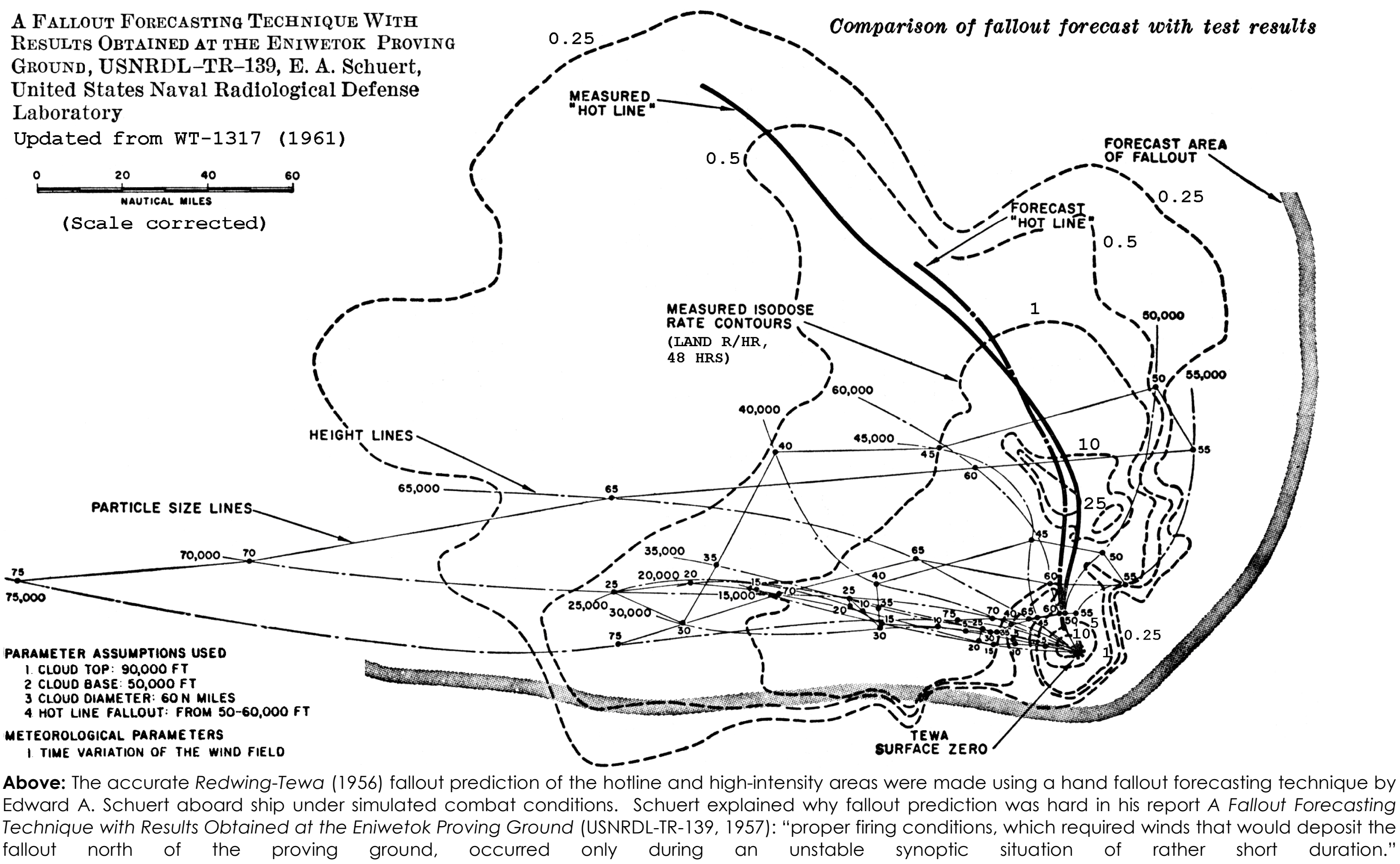
Zuni fallout gamma ray spectrum measured at 10 days after detonation, 13 miles downwind (sample How F-61 GA)*

Gamma ray energy (MeV)	**% of gamma rays emitted by fallout sample**
0.060	15.5
0.105	38.8
0.220	19.4
0.280	9.3
0.330	3.8
0.500	3.9
0.650	3.1
0.750	6.2
Mean energy	**0.218 MeV**

*W. E. Thompson, *Spectrometric Analysis of Gamma Radiation from Fallout from Operation Redwing,* U. S. Naval Radiological Defense Laboratory technical report USNRDL-TR-146, 29 April 1957, Tables 1 and 2. Note that this is the gamma ray spectrum actually measured for a fallout sample placed near the scintillation crystal of a gamma ray spectrometer, so it does not include the further reduction in gamma ray energy that occurs from Compton scattering in the atmosphere. Neutron-capture by U-238 in the *Zuni* weapon produced 0.31 atoms of Np-239 per fission and 0.20 atoms of U-237 per fission (USNRDL-466, 1961, Table 6). Np-239 and U-237 emit very low energy gammas. The production of Np-239 is inevitable in all nuclear weapons containing U-238 as an impurity in enriched uranium or as a neutron reflector or fusion stage pusher. U-237 production (which occurs when U-238 captures 1 neutron then emits 2 neutrons) requires high-energy fusion neutrons above a threshold of about 6.2 MeV, so it is produced in boosted and thermonuclear weapons.

Ocean water surface burst fallout is unfractionated so it emits slightly higher energy gamma rays. For example, R. L. Stetson's report *Operation Castle, Project 2.5a, Distribution and Intensity of Fallout,* WT-915, 1956, on page 145 states that the measured mean gamma ray energy of a fallout sample from the 13.5 Mt 52% fission *Castle-Yankee* ocean surface burst was 0.344 MeV at 8 days after detonation. Nevertheless, this is still substantially less than the 1.25 MeV mean energy of the cobalt-60 gamma rays assumed in most protection factor calculations, and is only about half of the 0.7 MeV figure mentioned by Glasstone. According to page 144 of weapon test report WT-915, the *Castle-Yankee* U-238 neutron capture nuclide abundances are similar to those for *Castle-Bravo* in Figure 19 above. Both *Bravo* and *Yankee* used the same fusion fuel, lithium deuteride enriched to 37% lithium-6, although the bomb designs were different (*Yankee* was identical in design to *Romeo* except for the fact that *Romeo* used non-enriched lithium, which is 7.42% lithium-6, the remainder being lithium-7).

Gamma ray spectra for fission weapon Nevada tests during *Operation Plumbbob* are given in Table 4.1 of the report by Dr Kermit H. Larson, et al., *Distribution, Characteristics, and Biotic Availability of Fallout, Operation Plumbbob*, weapon test report WT-1488, ADA077509, July 1966, page 96. The mean gamma ray energy of fallout from the 74 kt *Priscilla* air burst at 100, 200, and 300 hours after detonation was 0.493, 0.583, and 0.626 MeV, respectively. The mean gamma ray energy of fallout at 100 hours after tower shots *Diablo* and *Shasta* (both of which only produced 0.10 atom of Np-239 per fission, according to USNRDL-466) was 0.505 and 0.577 MeV, respectively. Np-239 exerts its maximum percentage contribution to the radiation from fallout at about 100 hours or 4 days after a nuclear detonation where the overall decay rate of the fallout is roughly proportional to $(\text{time})^{-1.2}$.



Above: The accurate *Redwing-Tewa* (1956) fallout prediction of the hotline and high-intensity areas were made using a hand fallout forecasting technique by Edward A. Schuert aboard ship under simulated combat conditions. Schuert explained why fallout prediction was hard in his report *A Fallout Forecasting Technique with Results Obtained at the Eniwetok Proving Ground* (USNRDL-TR-139, 1957): "proper firing conditions, which required winds that would deposit the fallout north of the proving ground, occurred only during an unstable synoptic situation of rather short duration."